LECTURES

ON

ILLUMINATING ENGINEERING

LECTURES

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ILLUMINATING ENGINEERING

DELIVERED AT THE

JOHNS HOPKINS UNIVERSITY

October and November, 1910

UNDER THE JOINT AUSPICES OF

THE UNIVERSITY AND THE ILLUMINATING ENGINEERING SOCIETY

VOLUME I

THE JOHNS HOPKINS PRESS
BALTIMORE, MD.
1911

The Lord Baltimore Press
BALTIMORE, MD., U. S. A.

PREFACE

This Course of Lectures on Illuminating Engineering was given at the Johns Hopkins University, Baltimore, between the dates October 26 and November 8, 1910, under the joint auspices of the University and the Illuminating Engineering Society. The origin and objects of the lectures are clearly stated in the preliminary announcement of the course, from which the following quotation is made:

"The Illuminating Engineering Society recognizing the fact that there is an increasing demand for trained illuminating engineers, and that the present facilities available for the specialized instruction required are inadequate, determined, through an act of the Council of the Society, to encourage the establishment of a course of lectures on the subject of illuminating engineering. This course should have three objects: (1) to indicate the proper coördination of those arts and sciences which constitute illuminating engineering; (2) to furnish a condensed outline of study suitable for elaboration into an undergraduate course for introduction into the curricula of undergraduate technical schools; and (3) to give practising engineers an opportunity to obtain a conception of the science of illuminating engineering as a whole.

"Inasmuch as such a course is most appropriately given at a university where graduate instruction is emphasized, and as the Johns Hopkins University has regularly offered courses by non-resident lecturers as part of its system of instruction, and is now preparing to extend its graduate work into applied sciences and engineering, an arrangement has been effected by which the lectures will be given at this University under the joint auspices of the University and the Illuminating Engineering Society. The subjects and scope of the lectures have been proposed by the Society and approved by the University. The lecturers have been invited by the University upon the advice of the Society."

The lectures were attended by 240 men from various parts of the United States, many of them representatives of technical schools, gas and electric central stations, and manufacturing com-

panies. A large number of the attendants at the lectures also followed the course of laboratory work which had been arranged. The general interest in the course encourages the hope that these published volumes may serve to advance our knowledge of this new and important branch of engineering.

GENERAL CONTENTS

VOLUME I

LECTURES

PAGE

I. THE PHYSICAL BASIS OF THE PRODUCTION OF LIGHT. *Three lectures* 1
JOSEPH S. AMES, PH. D., Professor of Physics and Director of the Physical Laboratory, The Johns Hopkins University.

II. THE PHYSICAL CHARACTERISTICS OF LUMINOUS SOURCES. *Two lectures* 25
EDWARD P. HYDE, PH. D., President, Illuminating Engineering Society; Director of Physical Laboratory, National Electric Lamp Association.

III. THE CHEMISTRY OF LUMINOUS SOURCES. *One lecture* 93
WILLIS R. WHITNEY, PH. D., Director of Research Laboratory, General Electric Co.; Past President, American Chemical Society.

IV. ELECTRIC ILLUMINANTS. *Two lectures* 109
CHARLES P. STEINMETZ, PH. D., Consulting Engineer, General Electric Co.; Professor of Electrical Engineering, Union University.

V. (1) GAS AND OIL ILLUMINANTS, (2) INCANDESCENT GAS MANTLES. *Two lectures* 157
(1) ALEXANDER C. HUMPHREYS, M. E., HON. SC. D., President of Stevens Institute of Technology; Past President American Gas Institute.
(2) M. C. WHITAKER, B. S., M. S., Professor of Industrial Chemistry, Columbia University.

VI. THE GENERATION AND DISTRIBUTION OF ELECTRICITY WITH SPECIAL REFERENCE TO LIGHTING. *Two lectures* 237
JOHN B. WHITEHEAD, PH. D., Professor of Applied Electricity, The Johns Hopkins University.

VII. THE MANUFACTURE AND DISTRIBUTION OF ARTIFICIAL GAS WITH SPECIAL REFERENCE TO LIGHTING. *Two lectures* 277
(1) MR. E. G. COWDERY, Vice-President, Peoples Gas Light and Coke Company, Chicago, Ill.
(2) MR. WALTER R. ADDICKS, Vice-President, Consolidated Gas Co., New York.

VIII. PHOTOMETRIC UNITS AND STANDARDS. *One lecture* 387
EDWARD B. ROSA, PH. D., Physicist, National Bureau of Standards.

IX. THE MEASUREMENT OF LIGHT. *Two lectures* 411
CLAYTON H. SHARP, PH. D., Test Officer, Electrical Testing Laboratory, New York City; Past President, Illuminating Engineering Society.

X. THE ARCHITECTURAL ASPECTS OF ILLUMINATING ENGINEERING. *One lecture* 507
WALTER COOK, A. M., Vice-President, American Institute of Architects; Past President, Society of Beaux Arts Architects.

VOLUME II

LECTURES

XI. THE PHYSIOLOGICAL ASPECTS OF ILLUMINATING ENGINEERING. *Two lectures* 525
P. W. COBB, B. S., M. D., Physiologist, Physical Laboratory, National Electric Lamp Association.

XII. THE PSYCHOLOGICAL ASPECTS OF ILLUMINATING ENGINEERING. *One lecture* 575
ROBERT M. YERKES, PH. D., Assistant Professor of Psychology, Harvard University.

XIII. THE PRINCIPLES AND DESIGN OF INTERIOR ILLUMINATION. *Six lectures* 605
(1) W. E. BARROWS, JR., Assistant Professor Electrical Engineering, Armour Institute of Technology, Chicago, Illinois.
(2) L. B. MARKS, B. S., M. M. E., Consulting Engineer, New York City; Past President, Illuminating Engineering Society.
(3) MR. NORMAN MACBETH, Illuminating Engineer, The Welsbach Co.

XIV. THE PRINCIPLES AND DESIGN OF EXTERIOR ILLUMINATION. *Three lectures* 795
(1) LOUIS BELL, PH. D., Consulting Engineer, Boston, Mass.; Past President, Illuminating Engineering Society.
(2) E. N. WRIGHTINGTON, A. B., Boston Consolidated Gas Co.

XV. SHADES, REFLECTORS AND DIFFUSING MEDIA. *One lecture*... 885
VAN RENSSELAER LANSINGH, B. S., General Manager Holophane Co.

XVI. LIGHTING FIXTURES. *One lecture* 931
MR. EDWARD F. CALDWELL, Senior Member of Firm and Designer, Edward F. Caldwell & Co., New York.

XVII. THE COMMERCIAL ASPECTS OF ELECTRIC LIGHTING. *One lecture* 945

JOHN W. LIEB, JR., M. E., Third Vice-President, New York Edison Co.; Past President, American Institute of Electrical Engineers.

XVIII. THE COMMERCIAL ASPECT OF GAS BUSINESS WITH SPECIAL REFERENCE TO GAS LIGHTING. *One lecture*.......... 1009

WALTON CLARK, M. E., President of The Franklin Institute, Philadelphia; Third Vice-President, United Gas Improvement Co., Philadelphia.

LABORATORY EXERCISES

Lists of experiments in connection with the Lecture Course, together with the necessary bibliographies..........1041

CHARLES O. BOND, Manager of Photometric Laboratory, United Gas Improvement Co., Philadelphia.

HERBERT E. IVES, Ph. D., Physicist, Physical Laboratory, National Electric Lamp Association.

PRESTON S. MILLAR, Electrical Testing Laboratory, New York.

A. H. PFUND, Ph. D., Associate in Physics, The Johns Hopkins University.

INDEX 1047

I

THE PHYSICAL BASIS OF THE PRODUCTION OF LIGHT *

By Joseph S. Ames

CONTENTS

Lecture I

Physical Quantities and Measurements

Objects and general principles of physics.
Methods of assigning numbers to physical quantities.
- a. Measurement in terms of units.
- b. Indirect means, e. g., temperature.

Simple ideas.
- a. Intuitive: space and time.
- b. Experimental: e. g., force (illustrated by properties of matter).

Units of length, of time, of force; C. G. S.; English.
Derived mechanical quantities, and their units; e. g., density, pressure.
Measurement of length, volume, time, force, pressure.
Errors of instruments.
Discussion of observations.
Definition of electrical quantities, and their units.
Measurement of electrical quantities by portable instruments.

Lecture II

Energy and Thermal Phenomena

Definition of work and energy: mechanical illustrations.
Our temperature sense. Thermal phenomena.
- Thermal effects.
- Methods of producing these effects.
- Explanation in terms of energy.

Meaning of "Conservation of Energy."
- Illustrations: battery, dynamo, etc.

Discussion of temperature and its "measurement."
Discussion of modes of producing heat-effects: flames, friction, conduction, radiation, etc.
Radiation and absorption: Kirchhoff's law, "Black Body."
Measurement of energy.
- a. Rise in temperature.
- b. Mechanical means.
- c. Electrical method: Eit.

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* The lectures are based upon the author's text-book "General Physics," published by the American Book Co., New York.

LECTURE III

Radiation

Spectra of radiation.
- Dispersive apparatus.
- Detecting and measuring apparatus.
- Visible, ultra-violet, infra-red radiation.
- Continuous, discontinuous and absorption spectra.

Modes of producing radiation.
- a. "Temperature-radiation."
- b. Luminescence: fluorescence, electrical discharge, etc.

Color sensation.

Cause of color of natural objects.
- a. Body absorption.
- b. Surface absorption.
- c. Exceptional cases.

Extension of temperature scales by radiation methods.

LECTURE I

Physical Quantities and Measurements

Matter. Through our various senses, such as those of sight and hearing, we are constantly receiving sensations which we interpret objectively; i. e., we locate the cause of a sensation in a definite portion of space. We picture to ourselves the existence there of something which we call "matter"; and to a limited portion of space which contains matter we give the name "physical body." Matter may be divided into two great classes: that which is living, such as plants and animals, and that which is not, such as pieces of wood and glass, water and air. Physics is, broadly speaking, the science concerned with this second division of matter, which may be called "ordinary matter"; and phenomena occurring in connection with matter of this kind are called "physical phenomena."

The scientific study of a subject involves three distinct ideas; the discovery, the investigation, and the explanation of phenomena. The first two require no discussion here; but it may be well to state that by the words "to explain a phenomenon" is meant to determine its exact connection with other phenomena, to describe it in terms of simpler ones, and in this manner to reduce the number of fundamental ideas as far as possible.

In seeking for explanations of phenomena we assume either directly or indirectly, that there is a definite connection between consecutive events, of such a nature that if we are able to reproduce exactly a definite condition, the same effect will follow regardless

of the epoch of time or the location in space. We are justified in this belief by all of our experience and observations.

Ether. The careful study of the phenomena of light led philosophers, many years ago, to believe that there is present in space another medium for phenomena than that furnished by ordinary matter. It has become an accepted fact that throughout the vast regions of space, in the solar system and beyond, there is a medium permeating all ordinary matter and having many properties in common with matter and yet not identical with it. This is called "the ether." In order to explain many electrical and magnetic phenomena, and even to describe the phenomena of radiation, it is necessary to assume its existence.*

Physics. The object of physics may therefore be defined to be the attempt to determine the exact connection between phenomena, both in ordinary matter and in the ether, and to express these relations with as few hypotheses as possible concerning the nature and properties of either.

Physical Quantities. A physical quantity is one which we can imagine as capable of changing in amount, something to which we can assign a numerical value. Some quantities can be *measured,* others cannot. To measure a quantity, another similar one must first be chosen as a standard or unit, and then the number of times this is contained in the original quantity is its measure. Thus, a length can be measured in terms of an inch, a yard, a centimeter, etc., depending upon the choice of unit. It is possible to understand the meaning of a zero value of any measurable quantity; further, two or more measurable quantities of the same kind, for instance two lengths, may be added. On the other hand there are many physical quantities which cannot be measured; and yet it is possible to give them numerical values. Thus, the temperature of a body cannot be measured, although it is possible by measuring the change in volume of mercury in a thermometer to give a number to temperature.

Simple Quantities. To most physical quantities exact definitions can be given, but there are a few for which this is impossible; there are no simpler ideas in terms of which we can describe them. The question as to the exact number of these need not be discussed here, and in what follows the philosophy based upon Kant will be

* One should add that a new school of philosophy exists which looks at nature from a different standpoint.

accepted. According to this we divide our simple ideas into two classes; intuitive and experimental. The two intuitive ideas are those concerned with space and time.

1. A straight line, a polygon, or a solid figure bounded by plane faces, together with the ideas involved in assigning numerical values to lengths, areas and volumes are considered intuitive. That is, it is impossible to define what is meant by length; and the idea of two equal lengths admits of no ambiguity. We can choose a unit length arbitrarily and then, making use of a method of superposition, determine the number to be given any length. The same general method may be applied to areas and volumes.

2. In regard to time, we have a definite conception of what is meant by two equal intervals of time; certain physical phenomena appear to us to repeat themselves at intervals of time apparently equal, e. g., the vibrations of a pendulum or the balance wheel of a watch. We have no way by which we can *prove* that these intervals are equal, yet there is every reason for believing that these motions of a pendulum and of the balance wheel of a watch are exactly periodic; for at any instant the external conditions affecting the motion are exactly the same, so far as we can tell, as they were at a definite interval of time before. In order to give a number to an instant of time one must choose some periodic motion such as just described, e. g., a certain pendulum vibrating under definite conditions, and some arbitrary epoch of time from which to count the number of vibrations; the number of vibrations between the epoch and the instant for which a number is desired is this number.

Among the fundamental ideas of which we learn by means of our senses may be mentioned temperature, pitch of sound, and what we call "force." For instance, through our muscular sense we become conscious of certain definite sensations when with our hands or arms or bodies we perform certain experiments on matter. Thus, if a large stone is held in the hand we become conscious of a certain property of matter called its "weight"; if we change the motion of a body by means of our arms, e. g., if we throw a ball or stop one in motion, we become conscious through the same channel of a property of matter called "inertia." It is possible, of course, to hold a body suspended from the earth and to set a body in motion or to stop it if moving, by other means than by our muscles; thus a weight can be suspended from a spiral spring and hang at rest with reference to the earth, a compressed spiral spring

may, as in a toy gun, produce the acceleration of a bullet, etc. Under all these conditions which are in their nature identical with those brought about by our muscles we say, in ordinary language, that "a force is acting on" the body; but it should be borne in mind that this is simply a description, nothing more. In order to assign a numerical value to a force one follows the natural way of studying the simplest cases of forces one can have, and then using definitions and methods based upon these observations. The discussion of this subject forms that branch of mechanics known as dynamics.

The simplest mode of obtaining a unit or standard force, at least from the standpoint of the inhabitants of this earth, is undoubtedly as follows: 1. Select arbitrarily a certain piece of matter. 2. Suspend it from a fixed support by a cord. 3. Call the tension in this cord a unit force. It is easy to see how, by means of a pulley, it is possible to balance this force by an equal one obtained by suspending from the other end of the cord, passing over the pulley, another body which is added to gradually until there is a balance. Having thus obtained two equal forces one can obtain a force twice as great by balancing one body against the two used in the first experiment, etc. In this way a set of standard bodies may be obtained whose weights give forces equal to 1, 2, 3, 4, 5, etc., and then, if it is desired to give a number to an unknown force, this may be done by balancing it against a selection of these known forces.

One can discuss in a similar manner methods of giving numbers to temperature, etc., and this will be done in a later lecture.

Units. The science of mechanics is based upon our ideas of length, time and of force, and methods have been discussed showing how we can give numbers to all these quantities. It is seen, however, that in each of these methods certain steps are arbitrary, and that the number finally obtained depends upon the nature of this arbitrary step.

a. *Length.* In giving a number to a length the first step is to select a length to which we give the number 1 (if we use the inch, we have one value for the length, if we use the centimeter we have a different value, etc.). The scientific world agrees to adopt as its unit of length the one-hundredth portion of the length of a certain platinum rod, kept in Paris, when this rod is at the temperature of melting ice. The length of this rod under these conditions is

called a "meter"; and one-hundredth of this length is called a "centimeter." There are other unit lengths in daily use in this country and in England, but it is not necessary to discuss them.

b. *Time.* In assigning a number to an instant of time we saw that it was necessary to select a "time-keeping mechanism," such as a clock, and, secondly, to agree upon some definite instant from which to begin counting. The scientific world has agreed to adopt as its time-keeping instrument the earth itself as it rotates on its axis, and to use as the unit, in terms of which intervals of time are expressed, the "mean solar second." This quantity is the second of time referred to the "mean solar day," which is the average length for one year of the lengths of the solar days during that interval, a solar day being the interval of time between the two instants when the sun crosses the earth's meridian at any point. It is known that solar days differ in length, but pendulums may be made whose periods are such that they agree exactly with the earth in its rotations at intervals a year apart, and these clocks are used ordinarily as time-keeping instruments. Different epochs are chosen in different localities; these usually differ by one, two, etc., hours.

c. *Force.* In assigning a number to a force it was seen that the essential step was to select an arbitrary piece of matter; and here the scientific world has agreed to use a certain piece of platinum kept in Paris. When this body is suspended and allowed to hang vertically there is said to be "a force" in the string equal to the "weight of one kilogram." The thousandth portion of this force is called the weight of "one gram." In England and this country other unit forces are sometimes used, commonly what is called the weight of a "pound."

The unit force on the "centimeter-gram-second" (C. G. S.) system, as used in all scientific laboratories, is the force required to produce an acceleration of one centimeter per second per second in a piece of matter whose mass is one gram. This force is called one "dyne." The weight of one gram is very closely 980 dynes—it is not the same at all points on the earth.

d. *Pressure.* From these fundamental properties—length, time and force—numerous other quantities are derived, one of which should be mentioned here: pressure. By pressure we mean the force per unit area, and, of course, the number we obtain for any pressure depends upon our selection of units of force and of area.

Measurements. It is necessary to say a few words in regard to the actual measurement of, or methods of assigning numbers to, the physical quantities so far discussed; but it is easily understood that for any satisfactory discussion of the subject reference should be made to some laboratory hand-book.

a. *Length.* In the measurement of small lengths two methods are in general use; one, depending upon the use of a screw and divided head, the other upon the use of a vernier. In the measurement of greater lengths special precaution must be taken against changes due to temperature, flexure, etc.

b. *Volume.* Measurements of volume are made in one or two ways; if the volume to be measured has the shape of a simple geometrical figure, its linear dimensions are measured and its volume calculated; if the volume is irregular, or if it is that of an inaccessible space, a method is used depending upon our knowledge of the volume of mercury which is required to produce a definite weight at a definite temperature; e. g., the volume of a bulb may be determined by filling it with mercury, expelling the mercury, noting its temperature, and then weighing it.

c. *Time.* Methods of accurate measurement of time are too complicated to be discussed here. It is sufficient to note that there are several methods which give an accuracy of a minute fraction of a second.

d. *Force.* The general method of measuring a force is, as stated before, to balance it against a known force, or a combination of such forces. It is possible to buy sets of weights, or a spiral-spring balance, which will give results sufficiently accurate for all purposes.

e. *Pressure.* It is customary to measure pressures such as those of the atmosphere, of boilers, of water mains, etc., by balancing the pressure against a vertical column of mercury. An illustration of this method is furnished by the ordinary mercury barometer. Since this is the accepted method, the unit in terms of which pressures are most often expressed is that of "one centimeter of mercury," by which is meant the vertical pressure required to balance a column of mercury, at the temperature of melting ice, one centimeter in height, when the force of gravity is that which exists at sea-level at latitude 45 degrees. This is a perfectly definite unit, and its value is known in terms of the other units.

Errors of Instruments and Observations. In this brief reference to the measurements of these five quantities it is seen that

reliance must always be placed upon an instrument furnished by some instrument maker; e. g., a micrometer screw, a vernier scale, a set of weights, a clock, etc., and it should not be necessary to emphasize two facts in connection with these instruments. First, every instrument must, of course, be compared with the original standard, or with copies of it whose errors are known. It is for this purpose that in all civilized countries Bureaus of Standards exist where such comparisons may be made. Thus every testing laboratory in America has or should have standards of length and of mass, whose values are known accurately in terms of the Paris standards. But, even granting that the testing laboratory has these standards, there are many errors or uncertainties inherent in the use of every instrument, and a thorough study must be made of it before it can be used for purposes of measurement. Thus no screw has an absolutely uniform pitch, and the variations in this must be determined by known methods; no set of weights is accurate, and its errors must be learned; and similar statements are true in regard to every instrument. The first precaution therefore in the measurement of any quantity is to determine the true scale of the instrument, which is not by any means in all cases that assigned to it by the instrument maker, and also to learn the variations in this scale in different parts of the instrument.

Second, when an instrument is to be used for purposes of measurement it is not sufficient to simply make one observation, e. g., to observe once the reading on a micrometer of the diameter of a wire. It is necessary to repeat the measurement often. To begin with it is always possible that an error may be made in reading the figures on the instrument or in recording them. Again, when the same measurement is repeated, the measuring instrument being removed and then replaced, it is noted that as a rule a different reading is obtained. This does not mean that the quantity measured has changed or that the instrument used is defective, but simply that in the use of the instrument there are certain inherent errors which limit the accuracy to which it may be trusted, errors coming in part from the individual using the instrument, in part from the instrument itself, and in part from other causes. When a sufficient number of observations have been made one may calculate by known methods the most probable value to be attached to the quantity, and also learn something concerning the certainty with which this number may be regarded as approaching the true value.

The confidence felt in their measurements by certain observers, and their entire lack of appreciation of the need of ascertaining the probable errors and uncertainties involved, is little short of astounding to one accustomed to ordinary laboratory methods.

Electrical Quantities. It seems necessary in this, the first lecture of the course, to give a brief discussion of some quantities which will not be fully explained until later in the course. These are the various electrical quantities; and, of course, to most engineers they are all well known. In the history of electric currents many units have come to the front at different periods, and even at the present time the definitions are not the same in all countries. The differences, however, are so slight as to justify us in neglecting them in all ordinary cases. The definitions given in what follows are those in terms of which practically all the measuring instruments now in use are calibrated. The unit of resistance—the ohm—is defined to be equal to the resistance of a column of mercury at zero degrees, of uniform cross-section, of length 106.3 cms., and having the weight of 14.4521 grams. (This column then has a cross-section of almost exactly one square millimeter.)

The ampere—the unit of current—is defined to be such a current as flowing in a silver voltameter of a specified pattern deposits per second .001118 grams of silver.

The volt—the unit of e. m. f.—is defined to be such a difference of potential as will produce, when applied to a conductor whose resistance is one ohm, a current of one ampere.

One of the fundamental properties of current when flowing in a conductor is to develop heat in this conductor, and it is well known that a simple formula connects the heat developed and the electrical characteristics of the system. This matter will be discussed more fully in the second lecture.

In order to give numbers to the resistance of a conductor the current flowing in it and the difference of potential at any two points, various methods have been devised and instruments perfected. At the present time there are no instruments in common use in laboratories which have attained accuracy to such a remarkable degree as these. This is owing in large part to the epochmaking inventions of Siemens and Lord Kelvin in Europe, and of Weston in this country. Thanks to the efforts of these scientists we now have instruments for the measurement of volts, amperes and watts which are sufficiently accurate for most purposes. I may

be pardoned if I again emphasize the fact, however, that all instruments are imperfect and that uncertainty is attached to every observation.

LECTURE II

Energy and Thermal Phenomena

Work and Energy. We are all familiar with the use of the words "work" and "energy" in every-day language. They have been adopted in physics as names of certain physical quantities which admit of exact definition. Naturally these definitions have been made so as to coincide as nearly as possible with those every-day experiences which gave rise to the names originally. Thus, if a man raises a weight vertically from the ground, if he compresses a spring, if he throws a base-ball, he knows that he is doing work. The essential ideas in all cases of work are, first, the action of a force, and, secondly, a displacement in the direction of this force. Corresponding to these ideas the numerical value of work is defined to be the product of these two quantities, i. e., the value of the force by that of the displacement in the direction of the force. It is easily seen that in all cases in mechanics the results of a force are either to overcome another force or to produce acceleration (i. e., change of velocity of a piece of matter). Corresponding to these two types of forces there are two ways in which work may be done; first, when a force or opposition is overcome, as when a weight is lifted, a spring is wound up, a bow is bent, etc.; second, when acceleration is produced, as when a ball is thrown, a fly-wheel or grindstone is set in motion, etc. It is common experience that in all cases when work is done on a body, as when a weight is raised from the earth, a spring is wound, a body given acceleration, the body as a result gains the power of doing work itself. It is said to have gained "energy." If the work done on the body has been done in overcoming an opposing force, the body is said to have gained "potential" energy; whereas, if the work has been done in producing acceleration, the body is said to have gained "kinetic" energy. Potential energy is therefore always associated with a body in a strained or "unnatural" condition; kinetic energy, with motion, either translation or rotation. It is a matter of common experience also that in all cases of mechanical work one body loses energy and a second body gains it. Thus, if a bullet is expelled from a toy gun by means of the sudden relaxation of a

compressed spring, the bullet gains energy and the spring loses it. It is easy to show that for all types of ordinary mechanical forces the amount of energy lost by one part of the system—namely, that which is doing work, is numerically equal to the energy gained by another portion of the system, that on which work is being done; and, as a consequence, therefore, the total amount of energy in the system remains unchanged. It was recognized many years ago that there were certain apparent exceptions which were associated with friction. Thus, if a fly-wheel in motion is disconnected from the driving shaft, its energy—as shown by its motion—gradually decreases, as it comes to rest under the action of friction. Here, then, is a case of an apparent disappearance of energy. It was noted, however, that in all cases like this there were certain heat-effects produced; and it has been established that there is an intimate connection between the loss of mechanical energy and the resulting heat-phenomena. Before stating this connection, however, it may be well to say a few words in regard to our ideas of heat.

Heat-Phenomena. Our attention is called to thermal phenomena by means of our temperature sense. We possess in certain portions of the surface of our bodies nerve endings which are sensitive to thermal changes in our environment. That is, if we expose our hands to sunshine or bring them near a stove in which there is a fire, or to a flame, we experience a definite sensation, and we say that we feel warm. Whereas, if we put our hands on a block of ice, or if we allow some volatile liquid to evaporate from them, we experience a different sensation and say that we feel cold. The first step in the scientific investigation of these phenomena must be taken by exposing a piece of inanimate matter, such as a rod of iron, to the same conditions as those under which we felt warm or cold. When this is done, it is found that the piece of matter undergoes various changes; and these are called thermal effects. In ordinary language we speak of a change from a condition when we feel cold to a condition when we feel hot as being a change from low "temperature" to high temperature. Experiments show that when the temperature of a body is changed, all of its physical properties, with the exception of its mass and weight, are also changed. We select ordinarily from these thermal effects a few of the most obvious and the most important for purposes of study and observation. Among these may be mentioned change in volume, change in electrical resistance, and change in state, as, for instance,

when a piece of ice melts and becomes liquid. On examination it is found that whenever work is done against friction, heat-effects are produced, and the investigations of Joule led him to believe that the connection between these two phenomena was an exact one, which could be stated by saying that the amount of heat-effect produced depended simply upon the amount of work done against friction, i. e., upon the apparent loss of energy, and upon nothing else, not upon the time taken for the change, nor the temperature of the working parts, etc. As a matter of fact, if we consider various cases in which heat-effects are being produced, we see that in them all work is being done against the smaller parts of the body which experiences the heat-effect, in such a manner that the energy of these smaller parts is altered. As a consequence of various experiments, but notably those of Joule, the scientific world has accepted the belief that, when we are dealing with friction or similar phenomena, there is no loss of energy, but that simply the portions of matter with which it becomes associated are too minute for observation with our eyes, and therefore we do not observe by this means the effect produced, but that this effect is shown to us through our temperature sense or by some heat-effect. This statement means that one can apply a numerical value to the heat-effects produced, in such a manner that if it is introduced into the total value of the energy of a system, this total value remains unchanged no matter how much friction may take place in the system.

Conservation of Energy. This constancy of a certain number when applied to the energy of a system, including in that the proper figure to take into account heat-phenomena, is an illustration of what is meant by the principle of the conservation of energy. This principle was extended by Joule, Mayer and Helmholtz to include other phenomena than those of mechanics and heat. For instance, we know that, if we place some granules of zinc in a test tube and pour sulphuric acid upon them, there is a violent evolution of gas and the test tube gets warm. This experiment can be described in terms of energy by saying that the internal energy of the molecules of the zinc and of the acid furnish the supply necessary for the formation of the new molecules and also for the production of the rise in temperature. This experiment forms one of thousands coming under the head of Thermo-Chemistry, and all of these have resulted in justifying the above description of the experiment in terms of the internal energy of the various substances. We also

know that, if we take a test tube containing sulphuric acid and insert into it a strip of zinc and a strip of some other metal like copper, the two being joined outside the test tube by means of some wire, we shall then have what we call an electric current. This is an illustration of a primary cell. In this particular type of cell the zinc dissolves in the acid, and there is an evolution of gas; the chemical side of the experiment is exactly the same as in the previous test-tube experiment just described. It is observed, however, that in the second experiment, that with the primary cell, there is practically no change in temperature of the test tube. This means, in general language, that the energy previously used in causing a change in temperature is consumed in this case in producing the electric current. As a matter of fact, we all know that, when an electric current is passing in a conductor, the temperature of the latter is raised; and, if the conservation of energy can be extended to the phenomena of electric currents, we would expect to find on investigation that the energy consumed in the heating of the conductor by the current is exactly the same as that which is not accounted for in the heating of the test tube where the chemical reactions are going on. Complete investigations on this point justify this belief. Joule performed many interesting experiments to see if in return for a given amount of work he always obtained the same heat-effect regardless of the method and mechanism by which the latter was caused by the former; thus, by means of a steam engine, it is possible to turn a paddle in water and one can note the rise in temperature of the water, or by means of the same engine one can turn a dynamo, thus producing a current which can be made to flow in a wire immersed in water, and again the final effect is the rise in temperature of water. In all cases like this it is found that the conservation of energy is fully justified. As a consequence of these and countless other experiments it has become an accepted belief that the conservation of energy can be extended to all phenomena of both matter and ether.

Temperature and Thermometers. Before discussing questions of radiation and absorption as heat-phenomena it is necessary to say something in regard to temperature and the methods by which we are able to give a number to the temperature of a body. As we use the words hot and cold and speak of high temperature and low temperature in ordinary language, we are making use of ideas which come from our temperature senses, and therefore the tem-

perature of a body is a term which refers to its *relative* hotness. It is easily seen that this quantity cannot be measured, i. e., we cannot regard otherwise than as absurd such an idea as selecting a unit of hotness and determining how many times it is contained in the hotness to which we wish to give a number. The words themselves are nonsense. It is, however, evident that we can choose such a measurable property of some body as changes when the temperature of the body changes, and make use of the measured change in this as a means of giving a number to the temperature itself. For instance, we can select arbitrarily a certain copper rod, measure its length under some condition which can be easily repeated, such as at the temperature of melting ice, again measure its length when it is as another definite temperature, for instance, when it is immersed in steam under standard conditions, then measure its length at the temperature for which a number is desired. We can assign arbitrarily a certain number of steps or degrees to the interval between the temperatures of melting ice and of steam, say, 100; then an obvious method of giving a number to the temperature would be to take a proportion of 100 equal to the ratio of the change in length of the rod between melting ice and the unknown temperature to the change in length between melting ice and steam, i. e., $t = 100 \dfrac{l - l_0}{l_{100} - l_0}$. This system is based upon several assumptions which are justified by observations; namely, that the temperature of melting ice and of boiling water under standard conditions are the same at all points on the earth's surface, and at all times (this may be shown by proving that a body will always return to the same length when placed in a bath of ice and water, etc.); further, that the copper rod we have selected always attains the same length under the same thermal conditions. It should be noted, too, that this scale gives the number 0 to the temperature of melting ice and 100 to that of boiling water. (It is clear that this method of giving a number to temperature is practically the same as that which anyone would follow if called upon to give a street number to a house erected at some point in a block otherwise vacant.) It cannot be emphasized too often that we have devised a method for giving a number to temperature, and that we have not in any sense tried to measure temperature.

Some other observer might decide to take as his thermometer, or instrument for numbering temperatures, an iron rod and meas-

ure its change in length; or a glass bulb containing mercury and measure the apparent change in volume of the mercury; or a glass bulb containing some gas and measure the change in pressure of the gas, its volume being kept constant; or a platinum wire and measure the change in its electrical resistance; and so on. One of these methods is as good as another; each gives consistent results by itself; and, if several observers use instruments of the same kind, their readings are concordant. But the readings obtained for any one temperature by the use of different methods and instruments would all be different; and it is necessary for workers in scientific laboratories to come to an agreement as to which instrument they will use. The scientific world has agreed to adopt as the instrument for giving numbers to temperature the constant volume hydrogen thermometer. In various bureaus of standards throughout the world ordinary mercury thermometers may be compared with the standard instruments, so that the former may be used for ordinary purposes, as they are much more convenient.

It is clear that this definition of temperature applies only through the range of temperature over which we can make use of the hydrogen thermometer. When we come to temperatures so low or so high that there are serious defects in the use of the instrument, it is necessary to define other scales of temperature. For instance, at extremely low temperatures a helium thermometer may be used, or a platinum resistance instrument; and at high temperatures a scale of temperature based upon certain empirical laws of radiation may be adopted. In both these cases of the introduction of new scales of temperature the attempt is made to define them so that they agree with the gas temperatures at those moderately low and moderately high temperatures over which this gas scale can be used at the same time as the two new ones. In this way a certain continuity is obtained, but it must not be thought that we are extending the hydrogen-gas scale; on the contrary, we are introducing new scales.

Radiation and Absorption.—In text-books on physics one finds a full description of methods of producing heat-effects such as flames, friction, etc., and also a description of the various methods by which in general these effects are distributed from one point to another, as by conduction or radiation. In this course of lectures special emphasis must be laid upon the radiation process. This is illustrated when we expose our hands to sunshine and in many

other similar ways. It is known as a result of experiments, which need not be discussed here, that the essential features of the process are: first, an emission from one body of energy in the form of ether disturbances, second, the absorption of this energy by another body. It is known further that all bodies in the universe are emitting this energy. As a consequence, therefore, of these two facts the question as to whether there will be any heat-effect produced in a body owing to radiation processes depends upon two things; first, how much energy the body is losing; second, how much it is gaining. The phenomena of radiation and absorption of many bodies under different conditions have been carefully studied by many observers, and in the middle of the last century at about the same time a very important law was announced by Balfour Stewart in England, and by Kirchhoff in Germany. The statement is ordinarily called "Kirchhoff's Law." One form of it is to say that the radiating power and absorptive power of a body are identically the same in all respects at any one temperature; i. e., if a body under certain conditions radiates a certain type of energy more intensely than a second body, then the first body under the same condition will absorb that same type of energy more intensely than the second. (In the end this principle is an illustration of resonance.) In connection with this discussion of radiation and absorption Kirchhoff introduced the idea of a "black body," meaning by that a body which absorbs completely all radiations falling upon it; for, of course, in general, when radiation is incident upon a body part is reflected, part is transmitted, and only part is absorbed.

Temperature Radiation. When the radiation from bodies was more carefully studied it was found necessary to make certain limitations in the application of Kirchhoff's law. Kirchhoff himself applied it only to those cases where radiation was to be considered simply as a heat process, not as a chemical or electrical one, and recent experiments appear to prove that we are justified in using Kirchhoff's law only in the case of certain particular bodies under definite conditions. One way of defining this is to say that, if there is no change in the molecular constitution of a body when it is radiating energy, its temperature being maintained constant, then it obeys Kirchhoff's law; and the radiation from it is called "pure temperature radiation." Other types of radiation will be discussed in the following lecture.

It follows, then, that since a "black body" is the best absorber possible it is also the best radiator; i. e., at a given temperature it radiates more energy of any particular kind than any other radiator which obeys Kirchhoff's law; and it also follows, therefore, that all "black bodies" radiate alike and obey the same laws. If we can secure such a body, then, we have an instrument of great importance. Kirchhoff himself showed that, if a hollow body, such as a cast-iron shell, be maintained at a constant temperature, the radiation inside the space was that which is characteristic of a "black body" at the given temperature. If a small opening is made from without to the interior of such a shell, some radiation will escape; but the type of radiation inside will not be seriously affected; and, since, through the opening we receive on the outside the random radiation which is characteristic of the interior, we can secure in this manner what is practically a "black-body" radiator. The various laws which have been deduced for the radiation from such a body will be discussed in the next lecture.

Measurement of Energy and Power. So far nothing has been said in regard to the measurement of energy or the units in terms of which it is expressed. If we use the C. G. S. system of units, the standard of energy or its units is called the "erg"—i. e., the work done by a force of 1 dyne acting through 1 cm.—which is an extremely small quantity, so small that it is more customary to use 10^7 ergs as the unit. This amount is called a "Joule." If we are interested not simply in the amount of energy but in the rate at which it is delivered, we introduce the word "power" to signify the energy delivered per unit of time, and if the amount of work is one Joule per second the power is said to be one "watt." (On the English system the unit of work is the "foot-pound"; and the unit of power is a "horse-power," which is defined to be 33,000 foot-pounds per minute—this equals approximately 746 watts.)

There are three standard ways of measuring energy; by rise in temperature, by mechanical means, by electrical methods. A few words should be said in regard to the first and third. By experiments performed by Joule, by Rowland and by others we know accurately the amount of energy required to raise the temperature of water; and by the experiments of Regnault and many others we know the ratio between the amount of energy required to raise the temperature of water and that required to raise the temperature

of other substances. Consequently, if we can observe the rise in temperature owing to heat-causes of any body of known character, and of known weight, we know accurately the amount of energy supplied. Thus, if radiation falls upon a body and is totally absorbed, we have a means of measuring the amount of energy received.

In the case of experiments with electric currents we know that the energy consumed per second is equal to the product of the electro-motive force and the current; and the units of the ampere, the volt and the watt are so chosen that, if the electro-motive force as measured in volts is multiplied by the value of the current in amperes, the product is the number of watts of power furnished by the current. It is easy to see how by having this simple means of determining power through the operation of the electric current, we can make use of it for the general measurement of energy.

LECTURE III

Radiation

Radiation. By radiation we mean those disturbances in the ether which are being emitted by matter of all kinds and at all times. For a proper study of its nature we require instruments which analyze the radiation and which measure the quantity of energy in the radiation. It was observed by Newton that when the radiation from a small source of light was allowed to pass through a prism of glass it was broken up or "dispersed," so that the white light of the sun, for instance, was divided into many colors, each particular color corresponding to radiation leaving the prism in a definite direction. This process of analysis of radiation by means of a prism is called "dispersion"; and the investigations of Fresnel and others showed that what takes place is this; the prism transmits in definite directions trains of waves of definite wave-length; so that, whatever the nature of the incident radiation, that which is transmitted is distributed into regular groups, each group having a definite wave-length and leaving the prism in a definite direction. It was shown by Fraunhofer and others that one could secure dispersion by other means than by the use of a prism, as, for instance, by the use of a dispersion grating.

The apparatus by which the dispersion of light is studied is called a "spectroscope." It consists essentially of three parts: a

narrow slit through which the light enters; a prism or grating to cause the dispersion; a lens or concave mirror to focus the different streams of radiation on a suitable screen, where the detecting or measuring instrument is placed.

Spectra. When the radiation from any very hot source such as the sun or the carbons in an arc light is thus analyzed and spread out according to its wave-lengths, it is observed that only a small portion affects the eye. This is called "the visible spectrum." We see a broad band of light, colored red at one end, and violet at the other. In between these there are different colors, each merging imperceptibly into its neighbors. Certain colors have definite names; and we often speak of red, orange, yellow, green, blue, indigo, violet, as being the "colors of the spectrum"; yet we must remember that these colors are not isolated; the transition from red to violet is a gradual one. If a photographic plate is held in the region beyond the violet, it is affected intensely; and, if a thermometer is held in the region beyond the red, it shows by its rise in temperature that energy is falling upon it. We are thus accustomed to speak of the "ultra-violet spectrum" and the "infra-red." When the wave-lengths of the radiations causing in our eyes the color sensations are measured, it is found that a definite color is associated with a definite wave-length; and so we often speak of "red-light," etc., meaning radiation of such a wave-length as produces in our eyes the sensation of red, etc. The wave-length of the radiation in the extreme ultra-violet is the shortest of all; then, as the wave-lengths become longer, the blue end of the spectrum is approached; as it becomes still longer, the color gradually changes from blue to green, to red, etc., down into the infra-red.

Recording Instruments. It is not easy to find an instrument which will respond to waves of all wave-lengths, i. e., which will absorb them or will indicate the amount of the incident energy. For waves which are extremely short, much shorter than those which affect our sense of sight, we may use a photographic or a photoelectric process; through the visible spectrum we may also use a photographic process for the detection of the radiation, but for its quantitative measurement, either here or in the infra-red, we must use some modification of a thermometer. Various types of instruments have been devised and the problems are now fairly well understood. The four forms of instruments in general use are: *a*, the bolometer, which is a thin strip of blackened platinum whose

change in electrical resistance produced by the radiation is measured; *b*, the thermo-couple, or junction of two metals forming a closed circuit, whose E. M. F. as altered by the radiation is measured; *c*, the radio-micrometer, an instrument in which the thermoelectric current produced by the radiation flows through a small circuit suspended between the poles of a magnet, and can therefore be measured by the deflection produced; *d*, the radiometer, a modification in Crookes' original form of the instrument, depending upon the repulsion produced by incident radiation in a blackened disk suspended in a partial vacuum. Any one of these instruments, when properly calibrated, may be used to measure the energy of radiation.

Classes of Spectra. If the spectra of solids and liquids are studied, it is found in almost every case that there is a continuous spectrum, having its maximum in a region depending primarily upon the temperature of the source. On the other hand, if a gas is made luminous by the discharge through it of an electric current or by any other means, it is noted that its spectrum is discontinuous, i. e., is made up of isolated trains of waves. When the light from a white-hot solid is allowed to fall upon any body such as a piece of glass or a tank containing some liquid, a certain amount of the radiation is absorbed by the body, and if the transmitted radiation is analyzed by a prism or a grating the resulting spectrum is called "the absorption spectrum" of the body. It is obvious that the nature of this spectrum depends not simply on the body itself but also on the character of the source.

Temperature Radiation. In the preceding lecture some time was devoted to the discussion of the conditions under which Kirchhoff's law of radiation and absorption could be applied. It may be remembered that these conditions were as follows: If a body is emitting radiation and if its temperature is maintained constant by suitable means, then, provided there are no permanent changes produced in the body, it obeys Kirchhoff's law and the radiation which it emits is called "pure temperature radiation." The importance of this discussion and definition comes from the fact that for bodies which are emitting such radiations it is possible by applying certain general principles of physics to deduce theoretically certain relations between the temperature of the body and its radiation. Further, if the radiation from a "black body" is studied experimentally, certain empirical laws connecting gas temperature

and energy of radiation may be learned, and all "black bodies" radiate alike. This matter will be referred to more in detail towards the end of the lecture. It is extremely difficult to obtain pure temperature radiation, though we can approximate closely to it by the use of a "black body" such as described in the last lecture.

Luminescence. In general, however, when a body is emitting radiation there are changes going on in it even if its temperature is maintained constant by heating it from without; such bodies are said to be "luminescent." We have many types of luminescence and it may be worth while to say a few words concerning some of these. There is what is called "chemical luminescence," which is illustrated by the slow oxidation of phosphorus; there is "electro-luminescence" which we have when a gas is made luminous by an electrical discharge; there is "fluorescence," which is observed in many bodies and consists in the absorption of light of a certain wave-length, and in the emission of light of a different wave-length. The exact energy relation for the various cases of luminescence are not clear in all cases; nor is it possible to state any relations which connect the radiation with the physical properties of the source.

Photometry. The most obvious property of radiation is, of course, its power to affect our sense of sight in case the source has a temperature sufficiently high, or in case it is emitting waves sufficiently short. As has been said, we associate different colors with different wave-lengths, and the question therefore as to our color sensation depends primarily upon two things; the nature of the radiating source and the power of our eyes to recognize color. The physiological action of the eye is to be discussed in later lectures; and it may be sufficient to note here that the eyes of most people are competent to distinguish colors with great accuracy, provided the illumination is sufficiently intense.

The most important matter connected with radiation is the question of the energy carried by the trains of waves of definite wave-length. This can be investigated obviously by means of a suitable dispersive apparatus and a sensitive recording instrument, such as a bolometer or radio-micrometer properly standardized. But this is largely of theoretical importance. What we are most closely concerned with is the question as to the intensity of the effect of radiation upon our eyes. The investigation of the various problems connected with this forms the science of photometry. We must find suitable methods of comparing the efficiency of various sources

of light in producing light sensation; this implies a study of the intensity of the light sensation, of the energy required for this, and of that portion of the energy of the source which is radiated in the invisible portions of the spectrum.

Colors of Objects. We are concerned most often, however, not with the color of the source of light itself but with the color which natural objects appear to have when viewed in a certain light. We ordinarily call a leaf green, a brick red, etc., meaning simply that when viewed in sunlight these objects have these colors. If we study carefully many cases of colored objects we soon recognize that their color is in general due to one of two causes. The commonest of all causes is what is called "body absorption," and is illustrated perfectly by a piece of colored glass, a tank of colored water, flowers, etc. The process is as follows: The incident light penetrates into the body, where certain trains of waves of definite wave-lengths are absorbed, and where the rest of the light is either transmitted or is scattered in all directions by small inequalities or dust particles. Consequently, if one looks at the object either by transmitted light or from any direction, he will receive in his eye only that portion of the incident light which is left over after the absorption in the interior of the body. If the incident light is white, and if red light is absorbed by the body, it will appear blue, because when white light loses its red constituent it becomes blue. It is evident therefore that the nature of the color which an object appears to us to have depends vitally upon the nature of the light in which it is viewed, because we see in the end that light which is the result of subtraction from the incident light owing to absorption. The same body will appear to us of a different color, if the color of the source is changed. If the light after passing through one colored object is allowed to fall upon a second, and if we view this transmitted light we have, of course, a double subtraction. This is the process which we have ordinarily in the mixing of paints. The explanation of the color of a painted object is exactly that just given; the light enters a short distance and is scattered out, so that if two paints are mixed we have a double subtraction. It is hardly necessary to emphasize the importance of this general discussion of color in the question of the illumination in a room, i. e., the effect of the color of the walls, curtains, etc., upon the general illumination, etc.

There are certain objects, however, which owe their color to a process different from this, as, for instance, metals and the aniline dyes. In their case the incident light suffers absorption at the surface, not in the interior, and so their color is said to be due to "surface absorption."

There are many other exceptional cases of color about which nothing need be said at the present time, such as the colors associated with luminescence, interference, the scattering due to fine particles, etc.

Laws of Temperature Radiation. The most important type of radiation is, as has been said repeatedly, pure temperature radiation; and for many years many competent observers have been investigating the connection between the temperature of the "black body" emitting such radiation and the nature of the spectrum and the amount of the energy. It has been shown that, if all the energy emitted is measured by using a suitable absorbing instrument, the connection between the temperature of a source and the total quantity of the energy may be expressed by an extremely simple formula, namely,

$$\text{energy emitted} = a(t+273)^4,$$

where t is temperature on the gas scale, and a is a measurable constant, independent of temperature. This is called "Stefan's Law." This evidently furnishes a means of defining a scale of temperature in a region where a gas thermometer could not be used, since we can measure the energy emitted by bodies at all temperatures. The method, of course, is to take the law as given, which states the relation between gas temperature and energy over the extreme range to which a gas thermometer can be used, and *define* the temperature for regions of higher temperature by the formula itself. That is, we would measure the energy from a certain source and by the use of the formula deduce the value of the temperature. It should be clearly understood that there is no assumption involved in this; it is a matter of definition.

It has been found further that, when the energy of a "black body" has been dispersed into its spectrum, and the amounts of energy carried by trains of waves of definite wave-length are measured, there is also a connection between the distribution of this energy as a function of the wave-length and the temperature of the source, as measured on the gas scale. Several formulas have been

derived from these experiments; and here again we have a means of defining a temperature scale which can be applied to extremely high temperatures. All these scales defined by radiation formulas seem to agree to a high degree of accuracy.

One of these relations, known as Planck's law, may be written

$$E_\lambda = C_1 \frac{\lambda^{-5}}{e^{\frac{C_2}{\lambda T}} - 1}$$

where E_λ is the energy carried by waves whose wave-lengths lie between λ and $\lambda + d\lambda$, T is written for $t+273$, e is the base of the natural system of logarithms, C_1 and C_2 are constants.

Two other relations are:

$$\lambda_{max} T = \text{const.}$$

$$\frac{E_m}{T^5} = \text{const.}$$

where T is again written for $t+273$; λ_{max} is the wave-length corresponding to the maximum value of E_λ for the temperature T; and E_m is the value of E_λ at this wave-length λ_{max}.

II

THE PHYSICAL CHARACTERISTICS OF LUMINOUS SOURCES

By Edward P. Hyde

CONTENTS

Lecture I

1. Introduction.
   - A. What is light?
   - B. The conditions to be fulfilled by light sources.
   - C. The sources of supply and loss of energy.
2. Luminous efficiency.
   - A. Sensibility of the eye to energy of different wave-lengths.
     - a. Time relation between stimulus and sensation.
     - b. Sensibility a function of absolute intensity of illumination (Purkinje effect).
   - B. Luminosity curves for various illuminants.
   - C. Mechanical equivalent of light.
     - a. Unsatisfactory nature of ordinary definition.
     - b. Mechanical equivalent of most efficient monochromatic radiation ($M = 800$ lumens per watt).
   - D. Highest possible efficiency of *white light* (about 300 lumens per watt).
   - E. Highest possible efficiency of *black body* radiation (about 140 lumens per watt).
   - F. Quantities entering in discussion of *efficiency*.
     - a. Power supplied to lamp (Q).
     - b. Power radiated by lamp (R).
     - c. Power dissipated by convection (C_v).
     - d. Power dissipated by conduction (C_d).
     - e. Power radiated in visible spectrum (L).
     - f. Luminous flux in lumens (ϕ).
3. Quality of light.
   - A. Integral color of composite light.
   - B. Spectral distribution.
4. Temperature radiation.
   - A. *Black body* radiation.
     - a. Properties of the theoretical *black body*.
     - b. Quantity and quality of *black body* radiation at various temperatures.

c. Ratios of energy radiated in visible spectrum to total energy radiated $\left(\frac{L}{R}\right)$ at various temperatures.

d. Ratios of luminous flux to energy radiated in visible spectrum $\left(\frac{\phi}{L}\right)$ at various temperatures.

e. Ratios of luminous flux to total energy radiated $\left(\frac{\phi}{R}\right)$ at various temperatures.

f. Temperature of highest possible efficiency of *black body* about 6000° absolute.

B. Selective radiation.

a. No natural body is absolutely "black."

1. Difference in *emissivity*—"gray" bodies.
2. Difference in spectral distribution—"selective" bodies.

b. *Gray* bodies have same efficiency as *black* bodies at same temperature.

c. *Selective* bodies may have higher efficiency than *black* body at same temperature.

d. Metallic filaments as a rule owe efficiency in part to *selectivity*.

5. Luminescence.

A. Accepted definition of luminescence.

B. Query as to significance of term "luminescence."

C. Employment of terms in present lectures.

D. Types of luminescence.

a. Chemi-luminescence.

b. Photo-luminescence or phosphorescence.

c. Electro-luminescence.

LECTURE II

1. Introduction.
2. The physics of the electric incandescent lamp.

A. C^2R loss in leading-in wires.

B. Loss by thermal conduction and convection of gas negligible in commercial lamps.

C. Relation between loss through gas and pressure of gas for special platinum filament lamp at about 1700° absolute.

D. Loss by thermal conduction along leading-in wires and anchor wires not more than 5% for commercial tungsten and 7% for tantalum lamps.

E. Radiation arises from temperature and not luminescence.

F. Efficiency of metal filament lamp partly due to temperature of operation and partly to favorable selectivity. Osmium probably most selective of ordinary filaments.

G. Values of $\frac{L}{R}$ for incandescent lamps.

H. Relations between voltage, current and candle-power for incandescent lamps.

3. The physics of the arc lamp.
    A. Definition of "arc."
    B. Characteristics of arc discharge.
    C. Distribution of potential in the arc.
        a. Fall of potential at anode.
        b. Fall of potential along vaporous path.
        c. Fall of potential at cathode.
    D. Sources of luminous flux in the arc.
        a. Anode principal source of luminous flux in direct current open and enclosed arcs.
        b. The two electrodes equally the principal sources of luminous flux in alternating current open and enclosed arcs.
        c. The luminous vapor the principal source of luminous flux in "luminous" and "flaming" arcs.
    E. The difference between "luminous" and "flaming" arcs important from physical standpoint.
    F. Is luminosity of gas to be ascribed to selective temperature radiation or to so-called "luminescence"?
    G. Probable temperatures of anode, cathode and vapor in open carbon arcs.
    H. Conduction and convection losses in arc lamp not accurately known.
    I. Values of $\frac{\varphi}{Q}$ and $\frac{L}{R}$ for various types of arc lamps.
4. The physics of low pressure arcs and vacuum tubes.
    A. Distinction between arc and vacuum tube discharge.
    B. The ordinary mercury vapor lamp an enclosed luminous arc at low pressure.
        a. Efficiency ascribed to luminescence with large percentage of radiation in the visible spectrum.
    C. The mercury arc in quartz tube operated at higher current density and increased efficiency.
        a. Temperature radiation supposed to supplement luminescence in quartz mercury arc.
    D. Data on conduction and convection losses, and on values of $\frac{L}{R}$ for mercury arcs meager.
    E. In vacuum tube discharge the character of the light depends on nature of gas between electrodes.
    F. Owing to distribution of potential in vacuum tubes, long tubes are necessary for high luminous efficiency.
    G. Luminous efficiency of vacuum tube sources ascribed to luminescence.
5. The physics of open flames, and of the incandescent mantle.
    A. The ordinary open flame owes its luminosity to the temperature of carbon particles heated to incandescence.
    B. The temperature of Bunsen flame about 2100° absolute at its hottest part.

- C. The peculiar radiating properties of rare earths and their mixtures.
- D. Hypotheses that have been advanced to account for high efficiency of mantles.
  - a. Luminescence.
  - b. Localized high temperature due to catalysis.
  - c. Selective emission at temperature consistent with that of Bunsen flame.
- E. Most generally accepted theory at present that given under D—c, but question still in doubt.
- F. Peculiar phenomena of mixtures of thoria and ceria explained on basis of relative emissivities and selectivities of the two substances.
- G. Estimates of temperature of incandescent mantle.
- H. The luminous efficiency of mantle and values of $\frac{L}{R}$.
- I. Temperature of acetylene flame.
- J. The luminous efficiency of acetylene, and the value of $\frac{L}{R}$.

6. The physics of the Nernst glower.
   - A. The glower a "solid electrolyte," composed of oxides of rare earths.
   - B. Conduction, convection and other losses.
   - C. Probable temperature of glower.
   - D. The luminous efficiency of the glower and the value of $\frac{L}{R}$.
7. The physics of the fire-fly and other light-producing organisms.
   - A. The high efficiency of the fire-fly due to extremely selective luminescent radiation.
   - B. Light-giving properties of bacteria and other organisms.
8. The distribution of energy in the spectra of the various luminous sources.
   - A. Spectra of gases, liquids and solids.
     - a. Unique spectra of rare earths.
   - B. Energy distribution in visible spectrum of ordinary illuminants.
   - C. Energy distribution in infra-red spectrum of ordinary illuminants.
9. The quality of light from the various luminous sources.
   - A. Integral color and continuity of visible spectrum.
   - B. Colorimetric measurements of ordinary illuminants.

LECTURE I

1. *Introduction*

The sensation of *light* is produced normally when radiant energy transmitted through the luminiferous ether in electro-magnetic waves of sufficient amplitude, and within certain limits of wave-length impinge upon the retina of the eye. It is necessary to

keep in mind that the ultimate object of every luminous source is to produce the sensation of light, and that therefore the relation between the psycho-physiological sensation and the physical stimulus furnishes a fundamental criterion in an analysis of the physical characteristics of luminous sources.

However, the first condition to be fulfilled by a luminous source is that it radiate energy within the limits of the visible spectrum. This is the initial condition, but there are many other conditions, physical and non-physical, scientific and aesthetic, which determine the real efficiency of a luminous source, where by efficiency is meant the degree of adaptability to the required end. From a physical standpoint, the energy relations in the production of luminous energy are of prime importance. The interest centers in the efficiency of the transformation of the energy supplied to the lamp into the *light* received from it.

A definite amount of what is familiarly termed *chemical energy* is stored up in the molecules of acetylene and oxygen. After combustion a smaller amount of energy is stored up in the resultant molecules of CO_2 and water vapor, a part of the residue becoming available as *light*. The gross efficiency of the combustion of acetylene as a source of light is the ratio of the light produced to the energy stored up in the molecules of acetylene and oxygen before combustion, the two being measured in appropriate units. The energy stored up in the resultant molecules of CO_2 and water vapor may be considered as waste so far as the present transformation is concerned.

This example illustrates chemical rather than physical relations in transformation of energy, but serves to show that in many cases the two are intimately interconnected. Judged from a purely physical aspect the efficiency of the acetylene lamp depends entirely upon the ratio of the light produced to the energy liberated in the chemical transformation. Thus some of the energy is dissipated by conduction, some by convection and some by radiation. Of the latter a relatively small part is available as light. The matters of fundamental importance to the physicist, therefore, are the relations of the energy dissipated by conduction and convection to that radiated, the spectral distribution in the radiant energy, and the causes which determine these relations.

The incandescent electric lamp furnishes an interesting illustration. A definite amount of energy per second is supplied electrically

to the terminals of the lamp. A part of this is transformed into heat by the C^2R loss in the leading-in wires and junctions. The remainder is transformed into heat by the passage of the current through the high-resistance filament. That which is transformed into heat by the C^2R loss in the leading-in wires is completely lost, as far as its direct influence on the luminous efficiency of the lamp is concerned. This loss in the ordinary types of lamps manufactured at the present time is negligibly small, amounting in most cases to less than 1 per cent.

The energy which is transformed into heat in the filament is dissipated in various ways, only a small part of it ultimately becoming available for the production of light. A part of the energy is dissipated by conduction and convection by the gases in the bulb in cases where the vacuum is not high, but this loss in a good lamp is entirely negligible. Another portion of the energy is dissipated through heat conduction by the leading-in and anchoring wires. Thus, owing to the high temperature of the filament compared with that of the leading-in and supporting wires with which it comes into contact, there is a continual heat conduction away from the filament at these points, thus cooling the filament locally and decreasing its luminous efficiency.

The remainder of the energy transformed in the filament is radiated, the spectral distribution depending upon the temperature of the filament. Only that portion which is radiated in waves within the limits of wave-length of the visible spectrum is productive of light. As stated above, the loss due to conduction and convection by the gas in a normal lamp must be negligibly small. It is quite a simple matter, however, to show what a saving is effected in the case of an ordinary incandescent lamp through the use of an evacuated bulb. If a lamp is constructed having a filament of some material, such as platinum, which can be operated either in air or in a vacuum, the difference in power supplied to the lamp when evacuated and when filled with air, the temperature of the filament being the same in the two cases, is quite large. Thus a platinum filament of 0.1 mm. diameter and 15 cm. length, mounted in a pear-shaped bulb of 8 cm. maximum diameter and 13 cm. length, when operated at a temperature of approximately 1700° Abs. (Centigrade + 273°), requires 4.75 watts when the bulb is evacuated, and 24.3 watts when filled with air at atmospheric pressure. In other words, the loss by convection and conduction

of the gas is 400 per cent of the total power required to operate the filament in a vacuum.

The losses by conduction at the leading-in and anchoring wires have been variously estimated, the values found ranging from an almost negligible quantity to as high as 25 or 50 per cent in various types of standard lamps.[1] Attempts at direct measurement of the energy radiated seem to indicate comparatively high figures for the thermal conduction losses, whereas the conclusion from practical experience in lamp manufacture points to rather small losses. Preliminary measurements by a new direct method gave for these losses for normal carbon, tantalum and tungsten lamps values in all cases of the order of magnitude of 5 per cent, which would seem to be more consistent with the experience of lamp manufacturers than the much larger losses found by other investigators.

If then the losses by convection and conduction amount to but a small percentage of the total energy supplied to the filament, explanation of the relatively low luminous efficiency of the lamp must be sought in the spectral distribution of the radiated energy.

2. *Luminous Efficiency*

Of the energy radiated by a luminous source only that portion which lies within the wave-length limits of visibility produces the sensation of light. Even within these narrow limits the intensity of the sensation varies greatly with the wave-length when the retina is excited with equal quantities of energy. Thus a quantity of energy which in the deep red or extreme violet is scarcely sufficient to be visible, would in the yellow or green regions of the spectrum produce a moderately strong sensation.

The extreme wave-lengths which mark the limits of the visible spectrum are somewhat variable, depending on the individual. For normal eyes radiant energy between the limits of wave-lengths of $0.8\,\mu$ ($\mu = 0.001$ mm.) on the red side to a little less than $0.4\,\mu$ on the violet side produces the sensation of light. With moderately intense sources the eye can perceive rays of wave-lengths down to $0.38\,\mu$, but there is no sense of color beyond $0.4\,\mu$.

The energy contained in the visible spectrum of the radiation from an ordinary solid at ordinary temperatures comprises but a very small fraction of the total energy radiated. Beyond the visible on the red side, the *infra-red* spectrum extends from $0.8\,\mu$ to indefinitely longer wave-lengths, which have been isolated and studied

up to 96.7 μ.[2] It is in this region that in most cases the great bulk of radiant energy is emitted. Thus, in the case of the tungsten lamp about 95 per cent of the energy radiated by the filament is emitted in the form of heat rays of wave-lengths too long to excite the human retina.

Beyond the visible spectrum on the violet side the *ultra-violet* spectrum extends from about 0.4 μ or 0.38 μ to indefinitely shorter wave-lengths which have been isolated and studied down to 0.1 μ. The energy radiated in the ultra-violet region of the spectrum is for all ordinary sources very small, even compared with that radiated in the visible spectrum, and may generally be neglected in the following discussion.

It has been stated that the energy radiated in the infra-red and ultra-violet regions of the spectrum does not conduce to the sensation of light, and that even within the narrow limits of wave-length comprising the visible spectrum equal quantities of energy in different portions of the visible spectrum do not produce the same intensity of sensation. It is of much interest, therefore, and most pertinent to the question of the efficiency of light sources, to consider briefly the relation between the energy of the stimulus and the intensity of the resultant sensation for the various wave-lengths lying within the limits of the visible spectrum.

At the outset it is necessary to note that the intensity of the sensation does not depend solely on the intensity of the stimulus, even for any one wave-length. The time interval during which the stimulus acts determines, to some extent, the intensity of the sensation. There is a lower limit to the duration of the stimulus, below which no sensation is produced. As this time interval is increased the sensation rises rapidly for some wave-lengths even beyond that of permanent régime and then falls again to what has been termed the permanent régime, or normal sensation. All of this occurs within a fraction of a second. After the retina has been exposed for a long time to a constant stimulus, the sensation gradually decreases owing to *fatigue*. The element of time, therefore, plays an important rôle in determining the intensity of sensation for a given stimulus.

There is a second element which should be mentioned at the beginning as determining the relation between the intensity of the sensation and the intensity of the stimulus for different wave-lengths. If there have been found two quantities of energy in the

red and blue ends of the visible spectrum, respectively, which produce equivalent intensities of sensation where the absolute intensity of sensation is low, it does not follow that the two sensations will remain equivalent if the quantities of energy are greatly increased, even though each is increased by the same relative amount. The red sensation at the higher intensity would be relatively larger. This phenomenon is familiarly known as the Purkinje effect, and may be stated in general as follows: The relative intensities of sensation for equal energy excitation in different portions of the visible spectrum depend upon the absolute magnitude of the energy stimuli. In other words, the relation between the increase in sensation and the increase in stimulus is not the same for different wave-lengths in the visible spectrum.

In addition to these two elements of interval of duration and absolute magnitude of the stimulus in determining the relative sensations produced by equal quantities of energy in the different portions of the visible spectrum, there are other psycho-physiological elements which will not even be mentioned here. Moreover, the two elements which have been described briefly will not be considered further in the discussion. It will be assumed, (1) that in every case the stimuli act over a sufficiently long interval to produce the normal sensations of permanent régime; (2) that the absolute magnitudes of the stimuli are always moderately large, since it is only at relatively low intensities of illumination that the Purkinje effect is distinctly noticeable.

What, then, under normal conditions, is the relation between the intensity of the stimulus, and the intensity of the sensation in different portions of the visible spectrum? The answer is given in Figure 1.

The so-called sensibility curve which gives this relation is commonly obtained by determining the quantity of energy per second necessary in different portions of the spectrum to produce the same luminosity, i. e., the same intensity of sensation. The reciprocals of these quantities of energy are then plotted as the sensibility curve. The curve obtained in this way is shown in Figure 1. Neglecting the variations caused by the Purkinje phenomenon, the relative candle-powers of two sources may be computed by multiplying the ordinates of the spectral energy curves of the two sources by the ordinates of the sensibility curve, and comparing the areas enclosed by the two luminosity curves thus obtained.

Luminosity curves obtained in this way for a number of common light sources are given in Figure 2. Curves a, b, c, etc., are the spectral-energy curves for the 3.1 w. p. c. carbon lamp, the 1.25 w. p. c. tungsten lamp, the Nernst lamp, and the Welsbach mantle (99.25 per cent thoria, 0.75 per cent ceria) and curves a′, b′, c′, etc., are the corresponding luminosity curves, i. e., the curves showing the relative intensities of sensation produced in different parts of the spectrum. The energy curves are so drawn that the total energy in the visible spectrum (taken arbitrarily for this particular illustration as extending between the limits of wave-length $\lambda = 0.70\ \mu$

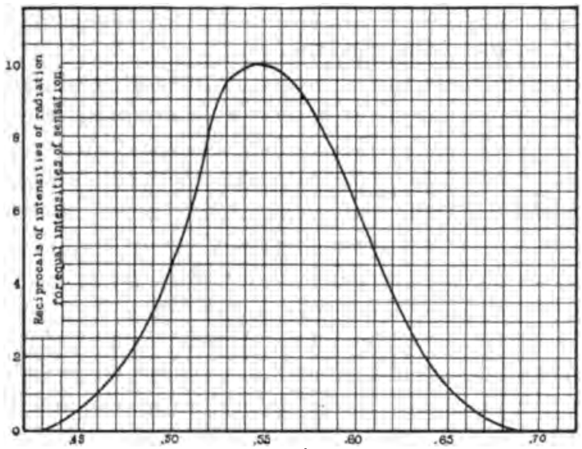

FIG. 1.—So-Called Sensibility Curve.
(Luminosity Curve for Equal Energy Distribution.)

on the red side to $\lambda = 0.43\ \mu$ on the violet side) is the same for all. In other words, the areas enclosed by the energy curves and the axis of abscissas, between the two limiting ordinates, are equal.

It is seen from an inspection of the luminosity curves a′, b′, etc., that although the eye has its maximum sensibility at $\lambda = 0.545\ \mu$, the wave-length of maximum luminosity for most sources is shifted well toward the red end of the spectrum, owing to the predominance of energy in the longer wave-lengths. Moreover, the wave-lengths of maximum luminosity for the various sources are somewhat different, as are also the shapes of the luminosity curves, owing to the different distributions of energy in the spectra of the various sources.

The literature on the efficiency of various light sources contains many reports of determinations of the *mechanical èquivalent of light*[3] where by this term is meant the energy per second within the limits of the visible spectrum which will produce a unit flux of light, measured photometrically—in other words the watts per

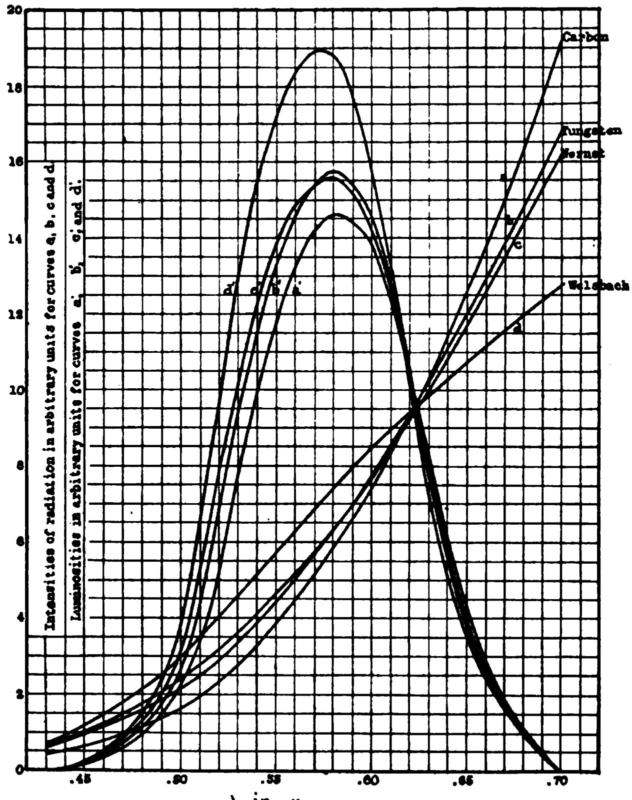

FIG. 2.—Energy and Luminosity Curves for Various Light Sources.

lumen. The determination of the mechanical equivalent of light is an attempt to correllate flux of energy, measured in watts, with the resultant sensation produced, measured in light units. As ordinarily determined, however, it is subject to criticism in two respects: (1) the value found for any light source depends upon the wave-lengths arbitrarily chosen as limiting the visible spectrum; (2) for any definitely chosen limits of wave-length, the value de-

pends on the light sources used. Both deficiencies arise fundamentally from the same cause, viz., that the mechanical equivalent of light is different for every color or wave-length, and therefore has definite significance only as applied to light of some one wave-length.

TABLE I

MECHANICAL EQUIVALENTS OF LIGHT AS GIVEN FOR SEVERAL ILLUMINANTS
(Wave-length limits taken as 0.38 μ and 0.76 μ.)

Source	Authority	Watts per Lumen
Hefner	Ångström	.0096
Arc	Drysdale	.0064
Nernst	"	.0095
Black body at 6000° Abs	Ives	.0080
Ideal yellow-green light	"	.0012

In Figure 2, curves a′, b′, etc., are luminosity curves corresponding to equal quantities of energy between the wave-lengths $\lambda=0.70\,\mu$ and $\lambda=0.43\,\mu$. The areas enclosed by these luminosity curves and the axis of abscissas taken between the two limiting ordinates might be taken as giving the relative values for the mechanical equivalent of light obtained from these sources. The values thus obtained, however, are not comparable with those usually given, because ordinarily the limits of wave-length are taken $0.76\,\mu$ and $0.38\,\mu$. But although it is true that visibility extends to these wave-length limits, the luminosity at the two ends is so small that it might be neglected. On the other hand, energy at the red end between $0.70\,\mu$ and $0.76\,\mu$ would constitute for most sources a large percentage of the total energy in the visible spectrum. In Figure 2 the narrow limits are taken, because for some of the sources given accurate energy curves to the larger limits were unobtainable.

In Table I some values of the mechanical equivalent of light for various sources, and between the customary limits of $0.76\,\mu$ and $0.38\,\mu$ are quoted.

Although the uncertainty in the actual values given may be great owing to the difficulty of measuring accurately by objective methods the small quantity of energy in the visible spectrum, the differences in the relative values obtained for different light sources are largely due to the fact that the mechanical equivalent for every different light source having a different spectral-energy distribution is necessarily different.

A much better definition of the term "mechanical equivalent of light" would be the flux of energy (in watts) for some definite wave-length—preferably the wave-length of maximum sensibility ($\lambda=0.545\ \mu$)—that produces a unit flux of light, measured photometrically (one lumen). From the best determinations of this quantity up to the present time the most probable value for $\lambda=0.545\ \mu$ is of the order of magnitude of 800 lumens per watt, or, as more commonly expressed, 0.015 watt per mean spherical candle, though these values may be in error many per cent. Hence the most efficient light source that could be imagined would be one in which all the energy supplied to the lamp is transformed into radiation, and all this radiant energy is concentrated in light of that wave-length ($\lambda=0.545\ \mu$) to which the human eye responds most intensely. The efficiency of this source would be 800 lumens per watt, or 0.015 watt per mean spherical candle.

This light, of the single wave-length, $\lambda=0.545\ \mu$, would, of course, not be white. Its color would be yellowish-green, and it would be very unsuitable for ordinary illumination both on account of its own color and also because of the unnatural appearance objects illuminated by it would assume. The question naturally arises, "What would be the highest possible efficiency of white light, if all the energy supplied to the source was transformed into radiation, and all this radiant energy was concentrated within the limits of the visible spectrum in such a way as to produce white light, where by white light is meant a distribution of energy in the visible spectrum similar to that in the spectrum of average noon-time sunlight?" The answer to this question is approximately 300 lumens per watt, or about one-third the efficiency of the most efficient monochromatic light. Expressed in watts per candle the specific consumption of the most efficient white light would be about 0.04 watt per mean spherical candle. If the limits of the visible spectrum were taken as $0.70\ \mu$ and $0.43\ \mu$ the corresponding figures would be 400 lumens per watt or 0.03 watt per mean spherical candle.

Compared with this the efficiency of those ordinary illuminants for which we can measure the power supplied in watts is extremely low. The flaming arc has an efficiency of about 50 lumens per watt, or 0.25 watt per mean spherical candle. The tungsten lamp has an efficiency of 8 lumens per watt, or approximately 1.6 watts per mean spherical candle (1.25 watts per mean horizontal candle). Expressed in another way, if the efficiency of the most efficient

monochromatic source is taken as 100 per cent, the efficiency of the most efficient white light is approximately 15 per cent, the efficiency of the flaming arc and tungsten incandescent lamp are, respectively, 6 per cent and 0.9 per cent.

The reasons for the relatively low efficiencies of artificial sources compared even with the most efficient white light are threefold, as indicated in the illustration of the incandescent lamp given in an earlier paragraph. (1) Not all the energy supplied to the lamp is transformed into radiation; some is lost by conduction and convection. (2) Only a small part of that radiated is contained in the visible spectrum. Much is emitted in waves too long to affect the human eye. (3) That part of the radiant energy which is contained within the visible spectrum is not distributed most advantageously. Granting that conduction and convection losses could be eliminated, the spectral distribution of the radiant energy is an outstanding factor to be reckoned with.

If we confine our attention to the case of the simplest radiating solid, viz., the *black body* (which see), the only opportunity offered to change the spectral distribution is the variation of the temperature of the radiator. It can readily be shown that if all the energy supplied to a lamp was radiated in the continuous spectrum of *black-body* radiation corresponding to the temperature of highest efficiency, the efficiency of the lamp would be approximately 140 lumens per watt, or 16 per cent of the highest possible efficiency of the most efficient monochromatic light, to which we assigned the arbitrary value of 100 per cent efficiency. In other words, this most efficient *black-body* radiator would be 18 times as efficient as the tungsten lamp. In passing, it is significant that the temperature of the *black-body* under this condition is that corresponding roughly to the temperature of the sun. In other words, a *black body* at the temperature to produce white light, is at the temperature of maximum efficiency for pure temperature radiation.

In the literature on the general subject of luminous efficiency,[4] various phrases indicating different ratios of power and light have been invented and used. The confusion that has resulted from the use of quite similar terms to signify distinctly different quantities suggests in the present treatment the confinement to an explanation of the important quantities involved, without any extended use of the complicated nomenclature. One of the more common expressions, the mechanical equivalent of light, has been referred to

already. But even this term, as was pointed out, is indefinite and unsatisfactory as ordinarily used. By the mechanical equivalent of light is meant the light value of radiant energy, where only that radiant energy is included which may call forth the sensation of light, i. e., that portion of the radiant energy which lies within the limits of the visible spectrum.

As has been stated in a previous paragraph, the indefiniteness in the mechanical equivalent of light arises from the fact that the mechanical equivalent for every wave-length of light, and hence for every different composite light, is different. The light value for any one wave-length is much more definite, and the determination of the light value for energy of the wave-length, $\lambda = 0.545\,\mu$, of maximum sensibility (at high intensities) is of prime importance as indicating the upper limit of efficiency theoretically obtainable. This quantity, which may be denoted by M, is not known accurately, but has an approximate value of 800 lumens per watt, or 0.015 watt per mean spherical candle.

The principal relations which excite interest in a study of the efficiency of light sources may be stated briefly. Given a definite quantity of energy supplied to a lamp: (1) What proportion of that energy is transformed into radiation, and what part is dissipated in other ways, being thus lost so far as its light-producing power is concerned? (2) Of that energy transformed into radiation, what proportion is contained within the limits of the visible spectrum, and is thus productive of light in varying degrees? (3) What is the light-giving power of that energy radiated within the wave-length limits of the visible spectrum, or, in other words, what is the mechanical equivalent of light for that particular lamp? Of these three relations the first is quite definite and of considerable importance, whereas the second and, consequently, the third are more or less indefinite owing to the ill-defined limits of the visible spectrum. If the red end of the spectrum is taken as $0.8\,\mu$ instead of $0.76\,\mu$ no appreciable difference would be observed in the light flux owing to the almost negligible luminosity of energy between these limits of wave-length. But the amounts of energy ascribed to the visible spectrum in the two cases would be different by many per cent for most ordinary light sources.

The greatest interest, from a practical standpoint, centers not in the individual steps of the above analysis, but in the resultant ratio of luminous flux available from a lamp in proportion to the

power supplied to the lamp. The various steps in the analysis are, however, of considerable importance in indicating for any light source its most pronounced deficiency.

The various relations can be represented briefly by the use of symbols. Let Q be the power supplied to a lamp, measured in watts; R the power radiated, measured in watts; L the power radiated within the visible spectrum (from $\lambda = 0.38\,\mu$ to $\lambda = 0.76\,\mu$ taken arbitrarily), measured in watts; and ϕ the luminous flux from the lamp measured in lumens ($4\,\pi$ spherical candles). The first of the three ratios given above is represented by $\frac{R}{Q}$, the second by $\frac{L}{R}$, and the third by $\frac{\phi}{Q}$. Under Q, the power supplied to the lamp, would come the power lost by conduction C_d, the power lost by convection C_v, and the power radiated R, so that $Q = C_d + C_v + R$. If the analysis is carried further, as in the illustration afforded by the combustion of acetylene, the total power involved in the reaction may be represented by Q', where $Q' = Q + C_h$, the latter symbol indicating the rate at which energy is stored up in the resultant molecules of CO_2 and H_2O. Although the ratio $\frac{\phi}{Q'}$ of resultant luminous flux to total power involved in the transformation would give the ultimate efficiency of the light process, such a definition would be comparable with that for an incandescent lamp in which not only the heat and other losses in the generation of electric power, but even the chemical reactions in the fire-box under the boiler * are included in the energy supplied. Such an elaborate analysis would take us beyond the logical limits of a discussion of the *physical characteristics of light sources*, and hence will not be attempted in these lectures.

This general discussion of the elements entering to determine the efficiency of light sources is intended to prepare the way for the more detailed discussion of definite light sources in the second lecture. Under the treatment of each source the data on efficiency will be given, in all possible cases. Apart from the mere analysis of the efficiency or inefficiency of light sources, our interest should carry us further into the study of the causes which underlie the

* To make the analogy complete it would be necessary to consider the energy relations in the generation of acetylene, since this is a manufactured product.

phenomena exhibited by the lamps. Much valuable knowledge is gained from a study of radiation, the laws of radiation and the radiating properties of matter.

3. *Quality of Light*

In the previous lectures in this course, a discussion of color of natural objects was given. In this discussion it was assumed that the incident light was white light, normally produced, as in the case of sunlight. A quite different question, and one of distinct importance to the illuminating engineer, is that of the quality of the light furnished by various types of luminous sources.[3] The quality of the light manifests itself in two ways: (1) in the color of the light itself, when the lamp is viewed directly, or in the apparent color of white objects when seen illuminated by the light; (2) in the apparent colors of various differently colored objects when seen illuminated by the light. Both of these manifestations can be predicted for any light when its spectral composition is known.

Two lights may both appear white and yet have quite different spectral compositions. Taking average mid-day sunlight as standard for white light, an ordinary solid body, such as carbon, would emit a white light if it could be heated to a temperature of 5000° or 6000°. The spectrum of such a body would be continuous, and approximately the same as that of a theoretical *black body* (which see) at the same temperature.

On the other hand, a white light can be obtained by the admixture, in the proper proportions, of red, green and blue light, if for these three colors the right wave-lengths are chosen, or by the admixture of properly chosen pairs of spectral colors. From a mere visual inspection of the luminous source itself, or of a white surface illuminated by it, it would be impossible to tell the true nature of the white light. But if objects of various colors, when viewed under normal daylight, are illuminated successively by the light from the two apparently white sources, they would appear quite different under the two lights. Illuminated by the white light from the incandescent carbon at high temperature, the colored object would appear the same as when viewed in daylight. But when illuminated by the white light composed of three primary colors they would assume new and strange tints. It is not sufficient then to adjudge a light good or bad on the basis of its composite

appearance. A spectroscopic analysis is necessary to show whether the spectrum is continuous or discontinuous, and if discontinuous whether the discontinuity consists of a few bright lines scattered through the spectrum, as in the case of the mercury arc, or of a very large number of bright lines distributed throughout the entire spectrum, as in the spectrum of CO_2 at low pressure. A source with a discontinuous spectrum of the latter type is for most practical purposes equivalent to a source having a continuous spectrum of the same composite quality. In addition to the knowledge of the spectral distribution in the light from two sources of the same composite quality, it is of interest to study the composite qualities of the various illuminants. These differ greatly among themselves, in most cases the light being distinctly more yellowish than average daylight. The composite quality of any light may be expressed in terms of the quantities of three primary colors, red, green and blue, necessary for a match in color with the light under investigation, taking the quantities necessary to produce the white light of average daylight, as red 33 per cent, green 33 per cent, and blue 33 per cent.

In the detailed discussion of the various artificial illuminants in the next lecture, data will be given in all cases where such observations have been published, on the quality of the composite light, as determined by colorimetric measurements, and also on the distribution of energy in the visible spectrum as given by spectrophotometric analysis.

4. *Temperature Radiation*

Frequent reference has been made in the previous paragraphs to the various elements which enter to determine the ultimate luminous efficiency of any light source. As a first criterion for high efficiency it was found that the losses of energy by conduction and convection should be as small as possible, in order that most of the energy supplied the lamp should be transformed into radiation. But even though all the energy supplied to a lamp were transformed into radiant energy, the resultant luminous efficiency might range from 0 per cent to 100 per cent, depending upon the distribution of the energy in the spectrum of the radiating body. The study of radiation—the laws of radiation and the radiating properties of matter—is therefore of prime interest and importance in considering the physical characteristics of luminous sources.

It is necessary to distinguish two kinds of radiation: (1) *temperature radiation,* and (2) *luminescence.* Every body radiates energy at least in the form of heat radiation of long wave-lengths. If a body, during this process of radiation does not change its nature, it would continue to radiate in the same way if its temperature were maintained constant through the addition of heat. Such radiation is ordinarily known as *temperature radiation.* On the other hand, if a body undergoes change during the process of radiation, it would not in general continue to radiate in the same way, even though its temperature were maintained constant through the addition of heat. Such a process of radiation is known as *luminescence.*

Considering first temperature radiation, which plays an important rôle in determining the luminous efficiency of practically all ordinary illuminants, and which determines entirely the efficiency of electric incandescent lamps, it is necessary to introduce the idea of the theoretical *black body,*[*] or *complete radiator,* as it is sometimes called. All natural bodies show individual peculiarities in their radiation, and it is therefore desirable to refer back to some simple standard radiator.

We ordinarily call an object "black" which seemingly reflects little or none of the light incident on it. Exact measurement would show that each such object actually does reflect some light, and, moreover, in general that it reflects relatively more energy of some wave-lengths than of others. In other words, it reflects selectively.

A theoretical *black body* absorbs all the energy of every wave-length throughout the entire extent of the whole spectrum, i. e., it reflects none of the energy incident on it.

According to a law first formulated by Kirchhoff, and known by his name, the quantity of energy radiated per second by any body at any temperature is proportional to the absorptive power of the body at that temperature. Thus, given two bodies, A and B, such that at some definite temperature the coefficient of absorption for body A for energy of some definite wave-length is double the corresponding coefficient for B; then at the same temperature body A would radiate per unit area per second twice the amount of energy of the given wave-length radiated by B. Since the *black body* absorbs *all* the energy incident on it, it will conversely, at any temperature, radiate more energy of every wave-length per second than any natural body.

The relatively simple properties of the theoretical *black body* have inspired several attempts at theoretical deductions of the laws of *black-body* radiation. Moreover, in recent years the theoretical *black body* has been quite closely approximated by the use of a hollow cylinder insulated as far as possible from the surrounding air, and having a small aperture at one end through which the radiation from the interior walls of the cylinder escapes. Such a body, heated uniformly by an electric current, emits radiation approximating quite closely, both in quality and in quantity, that emitted by a true *black body* at the same temperature. Experiments carried out with radiators of this type have corroborated in a general way the *black-body* radiation laws deduced theoretically. There still remains, however, considerable uncertainty as to the exact values of the constants entering in the mathematical expressions of the laws, and in the case of the law of spectral distribution of energy at any given temperature the exact form of the law is not yet satisfactorily established. As a discussion of the laws of *black-body* radiation is included in another lecture of this course, they will not be given here. Constant reference will be made, however, to the properties of *black-body* radiation as a convenient standard with which to compare the radiation from natural bodies. Even though the radiation from a natural body may be due entirely to the temperature of the body, the quantity and quality of the energy radiated by material bodies at the same temperature depend on the nature of the bodies themselves. Only in the case of an absolutely *black body* is the radiation simply a function of the temperature.

Without introducing mathematical analysis it is instructive to consider briefly the changes produced in the quantity and quality of energy emitted by a *black body* corresponding to change in temperature. Such a consideration will conduce to a proper appreciation of the importance of attaining the highest possible temperatures if high luminous efficiency is to be secured. It has already been stated that the highest possible efficiency obtainable from a *black body* is but 16 per cent of the highest possible efficiency of monochromatic light. Moreover, even this is only obtainable at the extremely high temperature of 5000° or 6000°, a temperature far in excess of any that has as yet been realized in any lamp. It is of interest, therefore, to investigate the relation between the luminous efficiency and the temperature of a *black body* at various tem-

peratures. This relation depends on the relative amount of energy radiated in the visible spectrum compared with the total radiation, and on the way in which the energy in the visible spectrum is distributed.

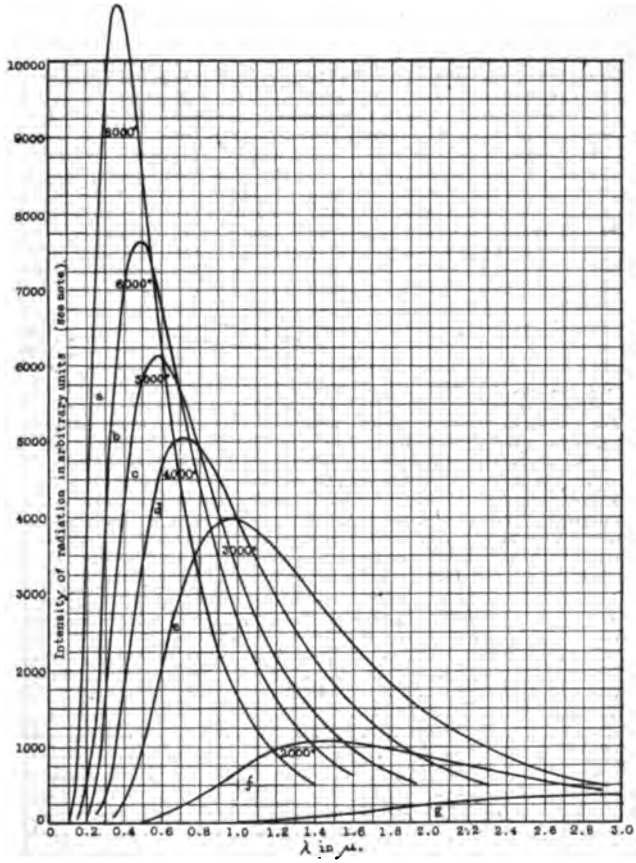

FIG. 3.—Energy Curves for a *Black Body* at Various Temperatures (Absolute).

NOTE—To obtain the proper relative intensities of radiation, the ordinates of curves b, c, d, e, f and g must be divided by 3, 6, 15, 50, 100 and 1000 respectively.

At very low temperatures the energy radiated per second in the visible spectrum is too small to affect the eye. As the temperature is increased the total energy radiated increases rapidly and the rate of increase is most rapid for the shorter wave-lengths such as affect the eye. Thus, at temperatures in the neighborhood of

1900° and 2100° Abs., when the temperature is increased 1 per cent the total energy radiated is increased 4 per cent, whereas the energy radiated in the visible spectrum is increased about 10 per cent or 15 per cent. Consequently, as a result of 1 per cent rise in temperature there is an increase of 8 per cent or 10 per cent in efficiency, i. e., in lumens per watt radiated.

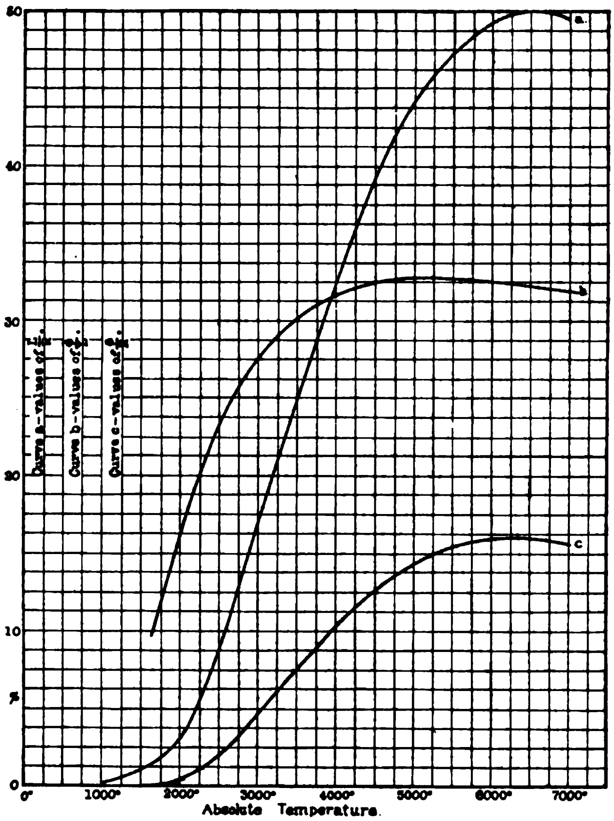

FIG. 4.—Values of $\frac{L}{R}$, $\frac{\phi}{L}$, and $\frac{\phi}{R}$, for a *Black Body* at Various Temperatures.

In Figure 3 are plotted curves showing the relation between energy radiated and wave-length for various temperatures ranging from 1000° to 8000° Abs. Below 1000° Abs. the energy in the visible spectrum is practically negligible. As the temperature is increased, relatively more and more of the energy is radiated in the visible spectrum, the position of the maximum emission shifting

constantly toward shorter wave-lengths. At a temperature of about 6000° the maximum lies in the visible spectrum, and approximately at that wave-length in the visible spectrum corresponding to the maximum sensibility of the eye.

As the temperature is increased beyond 6000° the maximum is displaced still further toward shorter wave-lengths, and the proportion of energy in the visible spectrum begins to decrease. There is, therefore, for a *black body,* a temperature of maximum efficiency beyond which the efficiency falls off again. Inasmuch, however, as all illuminants in present use which depend on temperature for their efficiency are operating at temperatures very much below that of maximum efficiency, any improvement which would make possible the use of higher temperatures would conduce to higher efficiency.

If the limits of the visible spectrum are taken as $\lambda = 0.76\,\mu$ on the red side, and $\lambda = 0.38\,\mu$ at the violet end, the ratio $\frac{L}{R}$ of energy radiated in the visible spectrum to total energy radiated by a *black body* at various temperatures can readily be computed. The results of such a computation are plotted in curve "a," Figure 4. The abscissae are temperatures, and the ordinates are the corresponding values of the ratio $\frac{L}{R}$. It is thus seen that for the arbitrarily chosen limits of wave-length of the visible spectrum given above, the greatest proportion of energy is radiated in the visible spectrum when the temperature of the *black body* is a little over 6000° Abs. Even at this temperature, however, the absolute value of $\frac{L}{R}$ is only 50 per cent.

It cannot be assumed *a priori,* however, that the highest luminous efficiency corresponds to the greatest value of $\frac{L}{R}$, for the distribution of the energy in the visible spectrum as compared with the sensibility curve of the eye determines to a large extent the lumens per watt radiated, i. e., the ratio $\frac{\phi}{R}$. In other words, $\frac{\phi}{R}$ is the resultant of the product of the two ratios $\frac{L}{R} \times \frac{\phi}{L}$, and the maximum of the product will agree with the maximum of one of the terms only in case the two ratios $\frac{L}{R}$ and $\frac{\phi}{L}$ have their maxima at the same temperature.

As has already been explained, $\frac{\phi}{L}$ is the ratio of the luminous flux measured photometrically to the corresponding energy flux (between the wave-lengths $\lambda = 0.38\,\mu$ and $\lambda = 0.76\,\mu$), measured in watts, and depends for its value on the distribution of the energy in the visible spectrum. If all the energy were concentrated at the wave-length of maximum sensibility ($\lambda = 0.545\,\mu$) the values of the ratio $\frac{\phi}{L}$ would be $M = 800$ lumens per watt. Calling this maximum value *unity,* the values of $\frac{\phi}{L}$ corresponding to a *black body* at various temperatures are given in curve "b," Figure 4. From an examination of this curve it is seen that for *black-body* radiation the ratio $\frac{\phi}{L}$ reaches a maximum at a temperature of about 5000° Abs., or not greatly different from that at which $\frac{L}{R}$ has its maximum. In other words, it so happens that for *black-body* radiation the temperature at which the largest proportion of the radiant energy lies in the visible spectrum, is also the temperature at which the distribution of energy in the visible spectrum is most favorable for the production of light. Since this temperature, 5000°-6000°, is approximately that of the sun and corresponds to *white light,* the conclusion follows that owing to the peculiar sensibility curve of the human eye, possibly due to inherited ancestral adaptation, the sun is at the temperature of highest possible luminous efficiency for a *black-body* radiator.

From an inspection of curve "b" in Figure 4, it is seen that even at the temperature of maximum efficiency the lumens produced by one watt radiated in the visible spectrum is only 33 per cent of the lumens that would be produced if all of the energy were concentrated at the wave-length ($\lambda = 0.545\,\mu$) of maximum sensibility. Multiplying the ordinates of curves "a" and "b" in Figure 4, there is obtained the value of $\frac{\phi}{R}$, $\left(\frac{L}{R} \times \frac{\phi}{L} = \frac{\phi}{R}\right)$, for a *black body* at various temperatures. This new curve thus obtained is plotted in curve "c," Figure 4. It is seen that the maximum efficiency obtainable from a *black body* (at the temperature of the sun) is only 16 per cent of the highest possible efficiency of monochromatic radiation.

Inasmuch as temperature plays so important a part in determining luminous efficiency, it is of interest to consider briefly the

possibilities in the employment of high temperatures as fixed by the melting points of available substances. The melting points of elementary substances seem to follow a periodic function of the atomic weights.[7] Thus, carbon, tungsten, tantalum and thorium all lie at periodic maxima of melting-point temperatures. The element which has the highest melting point is carbon, which has figured prominently in artificial illumination from the earliest days, as in flames and in the carbon incandescent and arc lamps. But the employment of carbon suggests another consideration which enters in the choice of a filament for use in an incandescent lamp. High melting point does not avail much if the vapor tension of the material is so high that the filament evaporates rapidly at moderately low temperatures. This element conditions the temperature practicable in an incandescent lamp, and although "flashing" and "metallizing" have tended toward reducing the vapor tension, and thus made possible higher working temperatures, the temperature that can be employed is still low compared with the melting point of carbon.

The oxides and silicates, particularly of the rare earth metals, form a group of highly refractory substances which have been employed in lamps (e. g., the incandescent mantle and the Nernst glower) partly because of their refractoriness and partly on account of the peculiar nature of their emission spectra.

We have seen that there is an upper limit to the possible efficiency of a *black body,* and that this upper limit is relatively low. Moreover, at present there are no means known for even approaching the temperature at which the highest efficiency is secured. What other possibilities are there, then, of obtaining high-efficiency lamps? Excluding luminescence, which will be discussed later, and confining our attention to temperature radiation, the answer to this question, if there is an answer, must be found in the phenomenon of selective radiation.[8]

So far as is known, no body in nature radiates precisely as a *black body.* No material body absorbs all of the energy of any wave-length incident on it; hence a *black body,* from its very definition, must, at a given temperature, emit more energy of every wave-length than any other body at the same temperature. Consequently, a material body may differ from a *black body* in that it emits per unit area at a given temperature a smaller quantity, as, for example, one-half or one-third of the energy of every wave-length of that emitted by the *black body* at the same temperature.

The energy curve of such a body would be identical with that of a *black body* except that its ordinates would be reduced proportionally throughout the entire spectrum. Such a body is sometimes known as a *gray* body. It can be realized experimentally by interposing between an experimental *black body* and the screen on which the radiation falls a rotating sectored disk. If the total aperture of the disk were 180° it would reduce by one-half the energy of every wave-length received from the *black body.* If the aperture were 90° but one-fourth of the energy of the *black body* would be received. In both cases the radiation received on the screen, i. e., the radiation emitted by the *black body* and sectored disk, considered as a unit, would be that of a gray body, that is, the same in quality but less in quantity than that of a *black body* at the same temperature. It is evident that there can be an infinite number of gray bodies corresponding to a *black body* at any given temperature. The various gray bodies would differ from one another and from the *black body* in total *emissivity.*

The importance of the distinction between the *black body* and the gray body arises from the fact that not infrequently the *emissivity* of a substance is cited in partial explanation of high efficiency. It is true that some substances which have low emissivities exhibit also the property of *selectivity,* which will be discussed presently, but it should be emphasized that mere *grayness* or difference in total emissivity has no direct influence on the efficiency of the radiation from a substance possessing this property. A gray body is no more or less efficient than a *black body* at the same temperature. The quality of the radiation is the same for both. The ratios $\frac{L}{R}$ and $\frac{\Phi}{L}$ would be identical for both. In the case of two filaments of the same size, one black and one gray, it would be necessary, in order to bring both to the same temperature, to supply more energy, say two or three times as much energy to the black filament as to the gray one. But the luminous flux obtained from the black filament would be twice or three times that emitted by the gray filament. It is a question of the difference between a 32 c. p. and a 16 c. p. lamp at the same watts per candle.

An indirect practical advantage in the use of substances having low emissivities in the manufacture of lamps is that, owing to the lower emissivity, filaments of larger size for any given candle-power may be used, thus making possible stouter and stronger

lamps. Another advantage is that the filament or mantle of lower emissivity would have a lower *intrinsic brightness* than a black filament or mantle at the same temperature.

But a material body can differ from a black body in its radiating properties in another way. Not only may the quantity of energy emitted be different from that of a *black body* at the same temperature, but the quality may also be different. Thus, if a body emitted one-fourth as much red, and one-third as much green, and one-half as much blue as a *black body* at the same temperature, it would not correspond to a gray body, but would radiate in a way that is known as *selective;* that is, it would radiate relatively more energy at one wave-length than at another compared with a *black body* at the same temperature. This type of *selectivity* is to be distinguished from that kind of selective radiation exhibited in the bright line spectra of luminous gases.

All substances which have been investigated show deviations from the ideal *black body* in respect both to the quantity and the quality of the radiation. It is therefore a matter of great interest and importance in the consideration of the physics of light production to study the radiating properties of matter, and, if possible, to correlate these with the other properties of elementary substances. Although much investigation has been directed toward the solution of these problems, the results obtained thus far are relatively meager. Universal agreement on the laws of *black-body* radiation, the simplest case, has not yet been reached, and the investigation of the peculiarities of the radiation from matter is but just begun.

It is beyond the scope of this lecture to discuss in detail the methods that have been employed, and the results that have been obtained in the investigation of the radiating properties of matter. Closely linked with the radiating properties of a substance are its reflecting properties, as formulated in Kirchhoff's law, and much valuable information regarding the radiating properties has been obtained by this indirect method, supplementing the results of direct investigation. The fundamental difficulty in arriving at definite conclusions regarding the radiating properties of matter at high temperatures is that of measuring the temperature. Methods have been employed, however, which indicate quite certainly in a qualitative way the relative selectivity of the radiation from various substances, and which, with the aid of some simple and probable assumptions, give an idea of the magnitude of the differences.

It is perhaps worth while to suggest at this time the practical importance of selective radiation. We have seen that differences in emissivity have only an indirect effect in the production of efficient lamps. A gray body is no more or less efficient than a *black body* at the same temperature. Selectivity, on the other hand, plays a direct, and possibly in certain cases an important, rôle in determining the efficiency of a lamp. Given a number of substances which can be operated at the same temperature, that substance would be most efficient as a luminous radiator, other things being equal, which radiated the largest percentage of energy in the visible spectrum and with the energy in the visible spectrum so distributed as to produce the greatest light effect. If a substance could be found which radiated all the energy in the visible spectrum, and so distributed as to produce white light, an ideal lamp would result. No substance has been found in which these conditions are approached, but investigation has shown that for some substances, e. g., the filament of the osmium lamp (which see), selectivity is of quite appreciable significance in determining efficiency.

From the standpoint of luminous efficiency that type of selectivity is of interest in which the emission in the visible spectrum is exaggerated compared with that radiated in other wave-lengths. On the other hand, substances exist which would be much less efficient as luminous radiators than a *black body* at the same temperature. For example, ordinary glass, if it could withstand the temperature of carbon filaments, would be much less efficient than a carbon lamp, assuming that the radiating properties of glass would not undergo serious change at higher temperatures. At ordinary temperatures glass absorbs very little energy in the visible spectrum compared with that absorbed in the deep infra-red. Conversely, glass emits relatively much less energy in the visible spectrum than a *black body* at the same temperature. Such a substance is ill-fitted to serve as a luminous radiator.

At the present time there are not sufficient data on the radiating properties of substances to justify any extensive classification. As a rule metals show relatively low-reflecting powers in the visible spectrum and uniformly high-reflecting powers in the infra-red. Conversely, such metals would show a relatively higher emission in the visible as compared with the infra-red spectrum, and would hence be more efficient luminous radiators than a *black body* at the same temperature.

In studying the incandescent mantle and the Nernst glower in the next lecture the peculiar form of the spectra of the oxides composing these radiators will be discussed. It has been proposed by some investigators that the radiation from these substances is not to be ascribed entirely to the temperature, but is due in part to luminescence.

5. *Luminescence*

If a body during the process of radiation undergoes a change in nature, it would not in general continue to radiate in the same way even though its temperature were maintained constant through the addition of heat. Such a process of radiation has been defined as luminescence. The cause of the radiation in this case is considered to lie not in the temperature of the system, but in some other source of energy. It is a simple matter to adduce illustrations of apparently typical luminescence, and of typical temperature radiation, but in many cases the distinction is difficult if not impossible. Even in apparently typical cases of luminescence it is a question as to whether the ultimate cause of the radiation may not be temperature—not the average temperature of the system, but the high localized temperature in isolated portions of the system.

The definition of luminescence that has been given is taken from Drude, and differs slightly from the original definition of Wiedemann, who first introduced the term. In the light of more recent experiments and more modern theory it is questionable whether either definition is illuminating or helpful to a better understanding of the phenomena. In the process of light production by the passage of an electric current through the filament of incandescent lamps we commonly say that the electric energy is transformed into *heat,* and that the filament is *heated* to such a temperature that it becomes incandescent. On the other hand, in the case of the luminous vapor in the arc discharge we frequently say that the vapor radiates by luminescence, and that there is a direct transformation of electric energy into radiation without the intermediate form of *heat* energy. And yet in this case, as in the other, there is some intermediate form of energy, viz., the kinetic energy of the corpuscles or ions which are accelerated by the electric force.

Whether or not there is any ultimate difference between temperature radiation and luminescence in true physical significance there

is unquestionably a marked difference in the apparent phenomena exhibited in the two cases. In the discussion of the various light sources in the second lecture following general custom the term luminescence will be used to describe that type of radiation which it is claimed by some *has never been produced* by *heating* the *system* * as a whole, but throughout the term will be used with reserve as to its exact significance.

Drude[4a] classifies under the general term *luminescence* the following phenomena: (1) *Chemi-luminescence,* as in the glow from slowly oxidizing phosphorus; (2) *photo-luminescence,* ordinarily known as *phosphorescence,* which is the after-glow resulting from previous radiant excitation; (3) *electro-luminescence,* as in the glow from Geissler tubes. Under *electro-luminescence* would also come the luminescence from the vapor in the arc discharge.

Lecture II

1. Introduction

In the preceding lecture a general discussion of the various elements which enter in a study of the physical characteristics of luminous sources was undertaken. In the present lecture the different types of illuminants will be discussed in regard to the various elements presented in the first lecture, so far as the peculiar natures of the different illuminants and the available data will permit. It is of interest to notice how investigation has been pursued along different lines for the different sources, making a well-balanced analysis difficult, if not at times impossible. It has been the aim in this lecture to consider each illuminant in the same general way, and at the same time to emphasize the peculiar and interesting physical properties of each.

Although in general the various physical properties of each illuminant are presented in the discussion of that particular illuminant, exceptions have been made in the matter of spectral distribution and quality of light, since it seemed that this information would be of more value when collected in a comparable manner. These questions therefore are discussed in separate sections at the end of the lecture.

* In a recent note in the Comptes Rendus (Vol. 130, No. 26, p. 1747; June 27, 1910) Bauer reports an experiment in which the characteristic bright line spectrum of sodium vapor was in his opinion obtained by heat.

2. The Physics of the Electric Incandescent Lamp[*]

In many ways the electric incandescent lamp is the simplest lamp that could be constructed, speaking from a physical standpoint. This is particularly true of the older form of untreated carbon lamp, since untreated carbon approaches quite close to the theoretical *black body* in its radiating properties. Untreated carbon has a high emissivity, and exhibits very slight indication of any selectivity in its radiation.

For the electric incandescent lamp in general it may be said that all the energy supplied to the lamp is transformed into heat, practically all of the energy into heat in the filament itself, since the resistance of the leading-in wires is in all practical cases quite small. Of the energy transformed into heat in the filament nearly all is radiated. As we shall see later the losses by thermal conduction along the leading-in and anchoring wires, and the conduction and convection by the enclosed gas at very low pressure, are very small in commercial lamps. Finally, the radiation is pure temperature radiation, there being no luminescence, and, in the case of the untreated carbon filament, the efficiency is due almost entirely to the temperature, there being no appreciable selectivity. The metal-filament lamps show marked evidence of selective emission, which in part determines their efficiency, but with this exception are quite similar to the untreated carbon-filament lamp in all respects.

In the introduction to the first lecture the incandescent lamp was cited to illustrate the principles involved in the physics of a lamp. In this illustration an experiment was described showing the tremendous losses that would result from conduction and convection by gas in the bulb. Under the conditions of the experiment which was performed upon a platinum filament (0.1 mm. diameter, 15 cm. long) in a pear-shaped bulb (13 cm. long and 8 cm. maximum diameter), the power required to bring the filament to a temperature of about 1700° Abs. when the bulb was filled with air at atmospheric pressure was found to be about five times that required to bring the filament to the same temperature in a vacuum.

The curves in Figure 5 show the relation between the required power and the pressure inside the bulb for the same platinum lamp and the same temperature. It is seen that the required power changes most rapidly at moderately low pressures, and that the loss due to the gas is still quite appreciable at pressures as low as 0.05 mm. mercury. It should be emphasized that the numerical

results found depend largely on the conditions of the experiment. A difference in size of bulb or composition of filament, or temperature of filament or composition of gas, would probably affect the numerical results to a marked extent. The curves of Figure 5 are given to show the general nature of the phenomenon.

As stated in a previous paragraph, this loss by conduction and convection of the enclosed gas in a commercial lamp is negligibly small. The vacuum that is secured in a good lamp is probably of

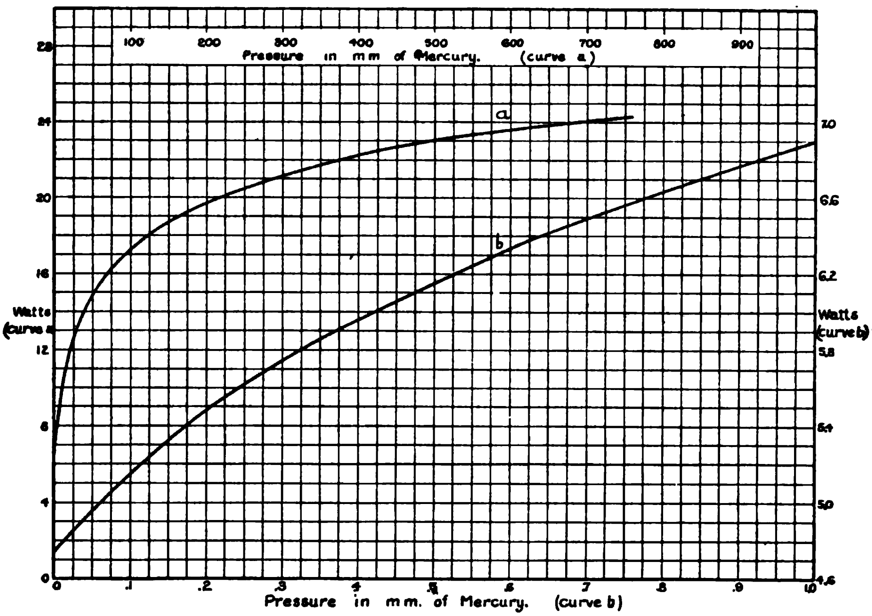

Fig. 5.—Watts Required at Varying Air Pressures to Maintain a Platinum Filament at a Constant Temperature (that of a Color Match with a *Black Body* at 1690° Abs.).

the order of magnitude of 0.001 mm. mercury, which is smaller than any vacuum measured in the described experiment.

The losses, on the other hand, by conduction away of heat at the leading-in and anchoring wires, though relatively small, are not negligible. Measurements of the total energy radiated, compared with that supplied, have led several investigators to the conclusion that as much as 20 per cent or 30 per cent of the supplied energy is lost in this way. Recent measurements on the temperature gradi-

ent of filaments near the leading-in and anchoring wires have led to the conclusion that the loss by conduction in an ordinary 1.25 w. p. c., 110-volt, 25-watt Mazda lamp is not more than 5 per cent. For a 2 w. p. c., 110-volt, 40-watt tantalum lamp the loss is less than 7 per cent. The larger loss for the tantalum lamp is due probably to the relatively larger number of anchor wires.

The differences in efficiency among the various incandescent lamps are to be ascribed therefore to the differences in the quality of the radiation.[10] Since there is no luminescence the quality of the radiation results from (1) the temperature at which the filament operates, and (2) the selectivity of the radiation corresponding to the filament material. Unfortunately, it is impossible to separate these two elements entirely. The measurement of temperature involves in general certain assumptions regarding the nature of the radiation, and the measurement of selectivity depends upon temperature relations. Methods have been devised, however, which give qualitative indication of the relative selectivity of the various filaments, and which on the basis of probable assumptions indicate the lower quantitative limits to the selectivity.

It is beyond the scope of these lectures to enter upon a discussion of the methods employed or of the detailed results obtained. The principal conclusions regarding the selectivity of lamp filaments which have been reached up to the present time may be stated as follows: If the various metal-filament lamps were operated at the same temperature as an ordinary untreated carbon filament at 4 watts per candle, then it is *probable* that owing to *selectivity* the tantalum lamp would have a higher efficiency than that of the carbon by *more* than 10 per cent or 12 per cent, the tungsten lamp would have a higher efficiency by *more* than 25 per cent or 30 per cent, and the osmium lamp would have a higher efficiency by *more* than 40 per cent. Of any of the metals, platinum, tantalum, tungsten or osmium, the last seems to differ most widely in the quality of its radiation from the *black body.* Both tantalum and tungsten give evidence of greater selectivity than platinum. Platinum deviates far from the *black body* in its emissivity, but, as explained above, this has only an indirect influence on its fitness for use as a lamp filament.

The efficiency of all the metal lamps is therefore probably due in part to selectivity. Only in the case of the osmium filament, however, is the selectivity so great that its high efficiency (1.5 w. p. c.),

as compared with a 3.1 w. p. c. carbon lamp, is almost entirely explained on the basis of the selectivity of its radiation. If the conclusions cited above are correct the temperature * of the osmium lamp is probably not very different from that of a flashed-carbon lamp at 3.1 watts per candle.

Inasmuch as practically all of the energy supplied to incandescent lamps is radiated, the ratio $\frac{R}{Q}$ is practically unity (more accurately about 0.95) for the ordinary commercial lamps. Hence, $\frac{\phi}{R}$ may be taken as $\frac{\phi}{Q}$, and is the ordinary luminous efficiency for the various types of lamps at normal burning expressed in lumens per applied watt. The values of $\frac{L}{R}$ may be taken roughly as ranging between 0.02-0.03 for a 4-watt carbon lamp, to 0.08-0.10 for a 1.25-watt tungsten lamp. Of course, the ratios $\frac{L}{R}$ and $\frac{\phi}{Q}$ can be modified at will by operating the lamps at different temperatures, i. e., at different voltages, but these cases do not have any interest to us at present except in so far as the relations between voltage, resistance and candle-power are of great importance in practical operation. On account of their importance in operation these characteristics will probably be considered in another lecture. Suffice it to say here that the temperature coefficients of resistance of the various filaments differ widely among themselves both in sign and amount, ordinary carbon, for example, having a negative coefficient at normal temperatures of operation, whereas tungsten and the other metals have relatively large positive coefficients. Moreover, owing to the peculiar radiating properties of the various filaments, there are marked differences in the changes in candle-power corresponding to a given change in total energy supplied.

3. The Physics of the Arc Lamp

The various types of arc lamps have been subject to much investigation, both as to their physical and operating characteristics. Many of the physical characteristics of the arc are so intimately

* Owing to the great discrepancies in the published values for the true temperatures of the different incandescent lamps, no attempt is made to give in this lecture a table of most probable values. References to original publications on the subject are given in the bibliography.[11]

connected with its operation that they will undoubtedly receive treatment in another section of this series of lectures. I shall therefore confine myself to a brief statement of some of the more purely physical characteristics of the arc.

The arc may be defined for our purposes as a portion of the circuit consisting of a pair of electrodes of solid or liquid material, electrically connected by a body of vapor which results from the volatilization of material from one or both of the electrodes. The term "arc" is sometimes used in a more restricted sense to apply to the bridge of vapor alone, and also in a still different sense to the *process* of the discharge or flow of current between the electrodes, rather than to the part of the circuit where it occurs.

If we connect a volt-meter to the terminals of an arc as used in lighting, we find that the volt-meter indicates a difference of potential of 40 volts or more, depending upon the type of lamp used. The difference of potential is determined by the current,[12] the distance between the electrodes, the materials of the electrodes and the pressure of the surrounding atmosphere. The fall of potential across the arc is not due to mere ohmic resistance, as in a wire carrying a current. Under certain special conditions an arc may be obtained in which the voltage increases with the current, but such is not a true arc as used in lighting. This kind of discharge is sometimes called a "glimm-strom." A distinct characteristic of a true arc is that as the current increases the voltage decreases. For this reason it is essential that arc lamps operated on constant potential supply circuits should be provided with series-ballast resistances to prevent the arc from short-circuiting.[13]

In the case of an ordinary incandescent lamp the fall in potential is practically distributed uniformly along the entire length of the filament, so that if we should measure the voltage drop along each centimeter of the filament we would find it to be the same throughout, and equal to that fraction of the total applied voltage which one centimeter bears to the total length of the filament. Such is not the case with the arc. The fall in potential takes place in three distinct steps: (1) at the anode, or where the current passes from the positive electrode to the gas; (2) along the vaporous path; and (3) at the cathode, or where the current passes from the gas or vapor to the negative electrode. The proportion of the total applied voltage which is taken up at each of these three places depends on the nature of the arc. In the ordinary short carbon arc[14] the

greater part of the fall of potential is at the anode, whereas in flaming arcs most of the electrical energy is transformed in the conducting vapor.

Corresponding to the three regions where the fall of potential takes place, with the corresponding transformation of electric energy, are the three distinct regions of luminous radiation, viz., the anode, the cathode and the vapor. And just as the distribution of the potential drop depends on the nature of the arc, so the distribution of the radiant energy varies greatly. In the case of the short, open, direct-current, carbon arc the gas or vapor contributes but a very small part[15] (several per cent) of the total luminous flux. The anode and cathode both are raised to a high temperature and consequently radiate energy, but the temperature of the anode is much higher than that of the cathode, and is to be considered practically as the light source in the open carbon arc. In the enclosed arc the luminous vapor plays a larger part in determining the luminous efficiency, but the principal source of light in the direct-current arc is again the anode. In alternating-current arcs the two electrodes play equal parts in producing the luminous flux, but as the two terminals are alternately positive and negative, and as relatively little heat is produced at the negative terminal, the average temperature of the carbon electrodes of an alternating-current arc is lower than the temperature of the anode in a direct-current arc, and hence the luminous efficiency of the former is less than that of the latter.

In direct-current and alternating-current open and enclosed carbon arcs the electrodes supply the larger part of the luminous flux, which therefore may be said to be due to pure temperature radiation. In the case of the *luminous* and *flaming* arcs the principal source of the luminous flux is the luminous vapor, the electrodes adding little to the luminous efficiency. The difference between these two types of arcs, *luminous* and *flaming,* is significant in its bearing on the physics of light production in these arcs. The essential difference between the two arcs consists in the two distinct processes by which the light-giving vapors find their way into the arc, where they perform simultaneously the two functions of conducting the current and radiating the light—two functions that are doubtless intimately connected. (1) A carbon arc may be used as a basis, the anode being impregnated with salts or pierced with a longitudinal hole through which a metal wire is threaded. This

gives the *flaming arc*. The anode is used because in the case of the carbon arc it is the hotter. The vapor is the result of the evaporation of the salts or metal, and takes part in the conduction of the current through the arc. The anode burns away rapidly as a result of the high temperature and consequent evaporation. (2) The vapor comes from the cathode. Such an arc is called a *luminous arc*. In it the anode may be entirely free from burning or melting away, being quite cool. There is necessarily a consumption of the cathode, but it may be rather slow.

The importance of the distinction between these two types of arcs enters in the consideration of the possible explanation of the high, luminous efficiency of the radiating vapor. Is this efficiency to be ascribed to pronounced selective temperature radiation at a high temperature or to luminescence? This is a much-mooted question, though the consensus of opinion at the present time seems to be that the efficiency is to be ascribed to luminescence rather than to pure temperature radiation.

The probability of this theory may be seen from the phenomena of the luminous arc. In the case of the flaming arc the metallic vapors get into the arc through evaporation at the anode, indicating at least as high and possibly a higher temperature than that of the anode. According to Violle [18] the temperature of the carbon flame is higher than that of the anode. With such temperatures it is not unthinkable that with vapors showing selective emission in favor of the visible region of the spectrum the luminosity might be due to selective temperature radiation rather than to luminescence. In the case of the luminous arc, however, the conditions are quite different. The anode may be entirely cold, the vapor being carried into the arc stream by the process of conduction. It is probable that the cathode is always fairly hot, but the evaporation of the cathode is unquestionably below that of the anode in the flaming arc. In the case of the luminous arc, therefore, there are perhaps greater difficulties in explaining the luminosity by temperature radiation, and, on the other hand, more cogent reasons for accepting the theory of luminescence.

Unfortunately, no data are available on the actual temperatures of the luminous gas in luminous and flaming arcs. On the other hand, numerous measurements of the temperature of the anode crater of a direct-current carbon arc have been made, and some little data on the temperature of the cathode and vapor have been pub-

lished." The most probable temperature deduced from these observations is about 3800°-4000° Abs. (Centigrade+273°). The temperature of the cathode has been found by Rosetti to be 3300° Abs., but as the same observer determined the temperature of the positive carbon to be about 4150° Abs. it is probable that his value for the cathode is 200° or 300° too high. For the vapor itself the value 5000° Abs. has been given. In the alternating-current arc the two electrodes have the same temperature, intermediate between the temperatures of the anode and cathode of the direct-current arc.

The arc lamp, like many other practical sources, is subject to losses of energy by conduction and convection. In addition, arc lamps operated on constant potential circuits are subject to still further losses owing to the necessity of series resistance or resistance as ballast. On constant-current circuits this ballast is unnecessary. The amount of loss in cases where lamps are operated on constant potential varies greatly in practice. As a rule the series resistance is not the least which would give stability, but is also made use of to adapt the arc to the existing supply voltage. Thus, in the case of a carbon arc operating on a 110-volt circuit, more than half the total energy is wasted in resistance. On account of the uncertainty of this loss and of the entire absence of it in constant-current circuits no account is taken of it in the data on efficiency given below.

With regard to the conduction and convection losses no data exist, so far as I know, which permit an accurate estimate of the magnitude of these losses. It is a well-known fact that the efficiency is increased by diminishing the thickness of the carbons, but the percentage loss through thermal conduction by the electrodes has probably never been determined. The fact that an arc is in contact with the air at atmospheric pressure would tend to make the loss by air conduction and convection great, but doubtless such an effect is much reduced by the fact that the radiation is proportional to a higher power of the temperature than the air loss probably is, so that in percentage it probably is much less than the loss with the Nernst lamp, for example.

Owing to the complicated nature of the production of light from the various arc lamps the available data do not permit the exact analysis of the energy relations such as is possible, for example, in the incandescent lamp. Thus we have seen that the temperature of the crater of a direct-current open carbon arc, which is chiefly

responsible for the efficiency of this type of arc lamp, is approximately 3800°-4000° Abs. A *black body* at this temperature, with no losses by conduction, convection, etc., would be about 8 or 10 per cent as efficient as the most efficient monochromatic source. Compared with this value the open carbon arc has an efficiency[18] of only about 2 per cent. In other words, if there were no losses except in the infra-red radiation from a *black body* at 3800° Abs., the ratio $\left(\frac{\phi}{Q} = \frac{\phi}{R}\right)$ of the luminous flux to the power input would be approximately 70 or 80 lumens per watt, whereas for the direct-current carbon open arc the ratio $\frac{\phi}{Q}$ equals approximately 12 or 15 lumens per watt. It must be borne in mind, however, that although the crater of the anode is at 3800°-4000° Abs., other parts of the anode near the tip, as well as the tip of the cathode, are radiating at much lower and hence much less efficient temperatures, so that a relatively large proportion of the supplied energy is radiated in the infra-red, compared with the radiation from carbon at 3800°-4000° Abs.

Similarly, whereas for carbon at 3800°-4000° Abs. the ratio $\frac{L}{R}$ would be approximately 0.30, the actual values found for various types of carbon arcs by Marks and by Nakano range from 0.08 to 0.17.

The efficiency of the alternating-current arc is roughly one-half to three-quarters that of the direct-current arc, whereas with flaming and luminous arcs efficiencies from three to five times that of the direct-current carbon arc have been obtained. Thus luminous efficiencies of 40-60 lumens per applied watt are found. Still higher efficiencies are possible in the use of electrodes exhibiting more pronounced selectivity in the visible spectrum.

Under the head of arc lamps should properly come the mercury arc, or mercury-vapor lamp, as it is more commonly called, but since in practice it is considered as a distinct type of lamp, and moreover resembles in some ways the vacuum-tube lamps, it will be considered in a separate section devoted to these two types of illuminants.

4. The Physics of Low-Pressure Arcs and Vacuum Tubes

The mercury-vapor lamp[19] is an arc at low pressure, and is to be distinguished physically from the nitrogen, carbon dioxide and other vacuum-tube sources with which, from its appearance, it might be

confused. The chief point of resemblance between the two types of lamps is that in each case the light is emitted by a luminescent gas or vapor at pressures considerably below that of the atmosphere. The distinguishing characteristic is the process by which the discharge through the tube takes place, with its effect on the nature of the radiation emitted. In the low-pressure mercury arc the conducting material is mercury vapor supplied by the hot, mercury cathode, and the character of the light is given by the emission spectrum of mercury vapor, just as in the luminous arc the cathode material enters the arc and determines the character of the radiation. The difference between the mercury arc and the ordinary luminous arc is mainly one of pressure of the surrounding gas.

In an ordinary vacuum-tube discharge, on the other hand, the conducting material is the gas between the electrodes, air, nitrogen, carbon dioxide, etc., and the character of the radiation depends on the emission spectra of these gases. The material of which the electrodes are composed plays no large part in determining the character of the light emission.

Considering first the low-pressure arc, as in the mercury-vapor lamp, the phenomena exhibited are in general the same as those presented in the discussion of ordinary arcs. There is the same fall of potential[20] at the anode and at the cathode, but owing to the low pressure in the tube the conductivity of the mercury vapor is much greater, permitting, or even necessitating, a much longer arc for high efficiency.

The temperature[21] of the mercury arc in a glass tube is apparently quite low, and the explanation of the efficiency is ordinarily ascribed to luminescence, with a relatively large part of the energy in the visible spectrum. The efficiency[22] of the arc, as ordinarily operated, is variously given as ranging between 12 and 24 lumens per applied watt, corresponding to 0.5-1.0 watt per mean spherical candle. By using quartz instead of glass it is possible to operate the lamp with a much higher current density and greatly increased efficiency.[23] It is probable that an efficiency of about 50 or 60 lumens per watt, corresponding to 0.20 or 0.25 watt per mean spherical candle, may be reached in the case of the quartz arc. It is believed, in this case that at high temperatures pure temperature radiation of increasing efficiency supplements the decreasing efficiency of the luminescent radiation.

Data as to the losses by conduction, convection, etc., and as to the ratio $\left(\frac{L}{R}\right)$ of the energy in the visible spectrum to the total energy emitted are somewhat meager and indefinite. Lux[24] finds for the Uviol (special kind of glass) and quartz lamps the values 0.058 and 0.176, respectively, for the ratio $\frac{L}{R}$. Moreover, for a Uviol lamp operating at about 0.65 watt per mean spherical candle, he finds that about one-half the total energy supplied to the lamp is radiated, the other half being dissipated at the electrodes, and by conduction and convection.

In the mercury arc, as in other arcs, the material of one or both of the electrodes determines the character of the light emission, whereas in an ordinary vacuum-tube discharge the nature of the gas between the electrodes determines the spectrum, modified, however, by such conditions[25] as pressure, potential gradient, etc. In the arc, after the gap between the electrodes is bridged, i. e., after the arc is "struck," the supply of "ions" or carriers of electricity is furnished by the negative electrode, and the conduction of current is continuous. The fall of potential at the electrodes of a vacuum tube is always very high, of the order of magnitude of several hundred or a thousand volts, so that the applied voltage must always be great. The fall in potential per centimeter length of tube is small compared with the fall of potential at the electrodes, and consequently very long tubes must be used in order that a moderate amount of the supplied energy may be radiated by the gas rather than practically all lost at the electrodes. The conductivity of the gas varies with the pressure,[26] reaching a maximum at pressures of the order of magnitude of tenths of a millimeter of mercury.

As in the mercury arc, the radiation is considered to be electroluminescence. The efficiency depends on the distribution of energy in the emission spectrum, which varies from gas to gas. Ångström[27] found for nitrogen a maximum of 91 per cent of the radiated energy lying in the visible spectrum, 69 per cent for carbon dioxide, and 60 per cent for hydrogen. Commercial installations, as in the Moore tubes, have an efficiency[28] of 5 or 6 lumens per watt for the nitrogen tube, and about one-third or one-quarter that value for the carbon-dioxide tube. The great discrepancy between the luminous efficiency of the radiation, and the actual luminous efficiency

of the lamp is to be ascribed to losses, of which those at the electrodes are by far the largest. Owing to the comparatively low temperature of the tube the conduction and convection losses are relatively small.

5. The Physics of Open Flames and of the Incandescent Mantle

The incandescent mantle lamp presents some of the most difficult problems in the physics of luminous sources. In addition to the problems connected with the mantle itself are those of the Bunsen flame, and these latter are so intimately interwoven with the inter-molecular, or so-called chemical processes in the flame, that it is impossible to undertake a complete discussion of the flame in a lecture of this nature. And yet there are certain physical properties of flame sources which must be mentioned briefly as auxiliary to a consideration of the incandescent mantle.

The open luminous flame was the earliest form in which gas was used as an illuminant, but the physics as well as the chemistry of the open flame has been the subject of much dispute, even in recent years. Various theories of the chemical transformations within the flame have been proposed with accompanying explanations of the light-giving properties of the flame.[29] The ultimate source of energy is chemical, but it has been a mooted question whether the radiation from the flame is dependent solely on the temperature or is due, at least in part, to chemi-luminescence. According to the theory generally accepted at the present time the light from the open luminous flame is due to the temperature radiation from finely divided carbon particles heated to incandescence by conduction from the hot gases of the flame. The spectral distribution[30] of the radiation is that which would be emitted by carbon at a temperature well within the accepted limits of temperature of the luminous zone, viz., 1500° Abs., at the beginning of the luminous zone and 2100° Abs. at the outer zone of complete combustion. The luminosity of the flame will depend on the number of carbon particles present, and the temperature which they attain. The causes which tend to increase or decrease the luminosity of flames may therefore be divided into two classes, (1) those that affect the formation and quantity of the carbon, and (2) those that determine the temperature.

The efficiency[31] of the open flame, considered from a physical standpoint is very low, but it is necessary to keep in mind the

essential difference between the conditions prevailing in the production of light in the open flame and in the electric incandescent lamp, for example. In the former the chemical transformations with the generation of heat take place in the flame itself, and it is difficult to separate the efficiency of the heat production from that of the incandescent carbon particles rendered luminous by the heat. In the case of the electric incandescent lamp the chemical transformations, with the resultant generation of heat, take place under the boiler where the adduced gas burns (supposing a gas engine), and there are large heat losses even in the most efficient systems. Moreover, there is a second loss when the heat energy is transformed into electrical energy which must also be considered. It is unquestionably true, however, that the efficiency of the open luminous flame, even in its most efficient form in the regenerative burner, is still very low. Owing to the large conduction and convection losses the heat available for rendering incandescent the carbon particles is not large, and the radiant efficiency of these, because of the relatively low temperature,[32] is comparatively small.

The open luminous flame has been very generally supplanted by the incandescent mantle, heated in a Bunsen flame. In the latter, which is particularly non-luminous, a mixture of gas and air is burned with the result that a more complete combustion takes place in the body of the flame. The temperature[33] of that portion of the flame between the slightly luminous bluish-green surface of the inner zone and the outer limits of the outer zone ranges from about 1800° Abs. at the inner zone to about 2000°-2150° Abs. at the outer zone. Although the maximum temperature of the Bunsen flame is perhaps but slightly if any higher than that of the open luminous flame, the average temperature of a large portion of the former is much greater than that of the latter, and the temperature to which finely divided solids placed in the Bunsen flame may be raised is much higher than any temperature available with the luminous flame.

Coming now to the incandescent mantle in its most common form, consisting principally of the oxides of thorium and cerium, various hypotheses have been proposed to account for its high luminous efficiency. Following numerous attempts at the use of metallic mantles, such as the platinum gauze of Gillard,[34] and in one or two cases of mantles of infusible oxides, as the basket mantle exhibited by Claymond in 1880,[35] and the Fahnehjelm[36] comb pat-

ented in 1885, Auer von Welsbach brought out his first mantle in 1886.[37] In his original patent application Auer mentioned various rare earths as particularly useful in securing light of various hues. Subsequently,[38] the mantle of approximately 99 per cent thoria and 1 per cent ceria as used to-day was developed.

Many years before the introduction of the Auer mantle the remarkable properties of certain of the rare earths when heated to incandescence. were known. Bunsen in 1864[39] discovered that didymium earth when heated gives not only a continuous spectrum, but also superimposed bright bands. Bahr in 1865[40] found a similar phenomenon in the case of erbium earth. Bahr and Bunsen[41] conjointly in 1866 made a further careful study of erbium oxide and came to the conclusion that the bright bands were emitted by the solid and not its vapor. Higginson, 1870,[42] confirmed these conclusions, investigating besides erbium a large number of other materials, and found these bright lines and bands in the spectra of lime, magnesia, etc.

The practical use of Auer mantles stimulated further research into the properties of the rare earths. In 1891 Haitinger[43] studied neodymium and praeseodymium, using mantles saturated with the nitrate solutions. He found that pure neodymium shows the phenomenon very weakly and praeseodymium not at all, but that the addition of 1 per cent or less of aluminum oxide brings out the bright bands in both cases. The marked effects produced by the addition of small quantities of one earth to another in greatly increasing the luminous radiation have led to the widely different views that have been taken in explanation of the efficiency of the incandescent mantle.

Without attempting a chronological treatment of the suggested hypotheses, it is interesting and important to mention briefly some of the theories[44] that have been proposed, principally because at the present time no one theory is universally accepted. One of the earliest theories accounted for the high efficiency on the basis of phosphorescence, and there are those of the present time who hold that, although temperature radiation enters, the peculiarly high efficiency is to be ascribed to some form of luminescence. For the most part, however, the theories have been based on temperature radiation, but the variations have arisen in attempting to explain the observed phenomena on this basis. According to one theory which held sway for a time the high temperature was produced

locally by a catalytic action of the particles of the mixture of ceria and thoria composing the mantles. Even at the present time catalysis in one form or another is suggested as the cause of the high efficiency.

The most probable theory, as accepted at the present time, was first proposed by Nernst and Bose, and afterward further elaborated by Féry. It is based on pure temperature radiation with selective emission, and suggests an explanation of the peculiar effects of mixtures which have made the problem so difficult of solution. Before outlining the theory the principal facts which seem to be fairly well established should first be presented. These facts are: (1) The temperature in the ordinary Bunsen flame probably does not exceed 2120° or 2140° Abs. at the region of highest temperature, and consequently could not account for the high-luminous efficiency of the mantle if the latter radiated as a *black body;* (2) the spectra of the rare-earth oxides are in general peculiar in exhibiting banded spectra; (3) when a small quantity of certain of the rare-earth oxides, as ceria, is intimately mixed with some other such rare-earth oxide as thoria, and the mixture in a finely divided state, as in the incandescent mantle, is heated in a Bunsen flame, the mixture has a much higher luminosity than either constituent separately; (4) the luminosity of the mixture of ceria and thoria depends greatly on the proportions of the two constituents present. As the ceria is increased from 0 per cent to 1 per cent the luminosity rises to about 10 or 15 times its initial value, but rapidly decreases again as the proportion of ceria is increased beyond 1 per cent; (5) the pure thoria mantle is probably at a temperature between 100° and 150° lower than that of the flame, and the addition of ceria causes a still further decrease; (6) thoria has a low emissivity, and no favorable selective emission in the visible spectrum, whereas ceria has a much higher emissivity and pronounced selectivity in the visible spectrum.

The theory most generally accepted as accounting for the phenomena exhibited by the mantle with varying proportions of thoria and ceria depends on the radiating properties of the two substances as given in (6). The mantle of pure thoria, owing to its low emissivity, assumes a temperature but slightly lower than that of the flame, but its luminosity is not great because the temperature is not very high, and thoria shows no favorable selective emission in the visible. The introduction of a very small quantity of ceria

lowers the temperature slightly because of the greater emissivity of ceria, but this decrease in temperature is much more than compensated for by the pronounced selective emission of the ceria in the visible spectrum. The integral effect therefore is to increase greatly the luminosity of the mantle. As the proportion of ceria is increased the luminosity constantly rises until the composition of the mantle is 99 per cent thoria and 1 per cent ceria, when the maximum luminosity is obtained. Further increments of ceria produce decreases in the luminosity because, owing to the high emissivity of ceria, the temperature of the mantle drops so low that the selective emission of the ceria is no longer sufficient to compensate for the decrease in temperature.

Although this theory is probably the one most generally accepted at present, it is still open to question, and certain facts point to the existence of catalysis, or luminescence, or perhaps both. The peculiar nature of the spectra of the rare earths makes the problem difficult, as ordinary optical pyrometry is likely to give quite erroneous results. Thus the temperature of the mantle[*] has been variously estimated from 1920° to 2470° Abs., and it is difficult to assign the correct value. The temperature of the Bunsen flame is by no means definitely established, and even if it were there would still be difficulties in arriving at the temperature of the mantle. Those physicists who subscribe to the catalytic theory would see no objection to assigning to the mantle a temperature in excess of that of the flame. If there is no excess temperature, the question still remains as to what extent the temperature of the mantle is lower than that of the flame. The use of very small thermo-couples by White and Travers has led to the value 2020° to 2120° Abs. as the maximum temperature of the Bunsen flame, and the same method applied to the mantle has indicated temperatures 100° or 150° lower. The excessively high values that have been suggested have been obtained from the use of optical methods which are subject to large errors in cases of such selective radiation as that exhibited by the Auer mantle.

In a similar way there is difficulty in determining the luminous efficiency of the incandescent mantle. White and Russell give as the consumption for the most efficient mantle containing 1 per cent cerium, 35 British thermal units per hour per candle (presumably measured horizontally). Since 1 B. t. u. per hour equals approximately $\frac{250}{60\times 60}$ calories per second, and 1 calory per second equals

4.19 watts, the watts per mean spherical candle (taking the spherical reduction factor equal to 0.88 as given by Lux) are $\frac{25\times 250}{60\times 60}\times\frac{4.19}{0.88}$ $=11$ watts per mean spherical candle, or approximately 1.1 lumens per watt. According to Fulweiler the most efficient incandescent mantle can be operated at 20 B. t. u. per candle, which would reduce the above values to approximately 6 watts per mean spherical candle, or about 2 lumens per watt. Lux gives for a mantle containing 0.8 per cent cerium practically the same values as those found by White and Russell for a 1 per cent cerium mantle, and for a mantle containing 0.1 per cent cerium he finds an efficiency of about three-fifths that of the 0.8 per cent cerium mantle.

As stated in an earlier paragraph regarding flames, the efficiency obtained as the ratio of the light produced to the heat energy supplied is not entirely comparable with the efficiency derived for an electric incandescent lamp by dividing the lumens emitted by the watts supplied, because in the generation of the electric power the efficiency of heat transformation is not 100 per cent. In a similar way the values given for the incandescent mantle are not comparable with those ordinarily given for electric lamps. If the analysis were carried back to the coal in each case a more accurate comparison could be made, but such an analysis is beyond the scope of this paper.

The ratio $\frac{L}{R}$, i. e., the ratio of energy radiated in the visible spectrum to total energy radiated has been found by White and Travers[46] to be 0.045, being quite close to the value 0.05 for the Nernst, as obtained from several determinations. The ratio of L to the total energy supplied is given by Lux[47] as 0.005, indicating that only about one-tenth the energy supplied is radiated by the mantle. The remainder must be lost by conduction and convection. These figures are given merely to show the order of magnitude of the various energy losses as far as the published results may be accredited.

Although no attempt has been made to give numerical values for open gas flames of ordinary illuminating gas, it may be well to mention briefly some of the characteristics of acetylene. Various values have been assigned for the temperature[48] of the acetylene flame, but it is probable that the temperature is not far from 2300° Abs. For $\frac{L}{R}$[49] the average of several determinations by

Ångström, Nichols and Coblentz, and Stewart, is about 0.045, the same as that given for the incandescent mantle. Similarly for the efficiency[60] Liebenthal quotes for ordinary burners an average specific consumption of 1.1 liters of gas per candle-hour with a possible minimum of 0.65 liter per candle-hour. Taking for acetylene the heating value given by Morehead[61] these figures lead to an average specific consumption of 19.3 watts per mean spherical candle with a minimum specific consumption of 11.6 watts per candle, corresponding to 0.65 and 1.1 lumens per watt, respectively. Lux gives for acetylene the specific consumption of 17.7 watts per candle, corresponding to an efficiency of 0.7 lumen per watt.

It is to be borne in mind that in all discussions of flames and mantles large discrepancies may arise owing to the nature of the burner used, or to the exact nature of the gas, or to the regulation of the gas in the burner. For these reasons only approximate values are attempted.

6. The Nernst Glower

Closely akin to the incandescent mantle and suggested by it, the Nernst glower nevertheless stands out uniquely from any other practical illuminant. Like the incandescent mantle it is composed of oxides of the rare earths, but unlike the mantle it is heated to incandescence by the passage of an electric current. The Nernst glower is what is known as a *solid electrolyte,* i. e., a substance which conducts electrolytically (as distinguished from metallically) when at a sufficiently high temperature. At ordinary temperatures it is an electric insulator.

The work of Nernst, which led to a patent application in 1897, was probably anticipated to a certain extent by Jablochkoff,[62] who in 1879 made an electric lamp whose radiating body was made of a small plate of kaolin, a portion of which was rendered incandescent by the spark-discharge current of an induction coil. The detailed patents of Nernst, given out in 1901, covered a number of combinations, involving the oxides of zirconium, thorium, cerium, erbium and yttrium, which may be used to make satisfactory glowers. According to an analysis given by Beebe[63] several years ago (1905), the regular commercial glower as manufactured in this country consists normally of 85 per cent of zirconia and 15 per cent of yttria, but from other descriptions that have been given it seems probable that erbia, thoria and ceria have at times been included.

It is an interesting fact that the pure oxides are not as satisfactory as are mixtures of two or more oxides, either from the standpoint of electrical conductivity or luminous radiation.

The energy relations in the Nernst glower are still to a great extent a matter of speculation. The destructive electro-chemical decomposition at the electrodes which accompanies electrolytic conduction is supposed in the case of the Nernst glower to be counteracted by the oxidizing action of the air. The glower consequently will not operate in a vacuum, and is hence subject to losses of energy by thermal conduction and convection of the air. Furthermore, it has been suggested[54] that since the atmosphere surrounding the glower is ionized and there is present a very appreciable potential gradient some of the energy supplied the lamp may be conducted electrically through the surrounding air and not through the glower body.

Regarding the losses through thermal conduction and convection in the air there are several published estimates.[55] According to Hartmann these losses amount to anywhere from 5 per cent to 70 per cent, depending upon the assumption on which the estimate is made. Lux gives the loss as about 30 per cent, and Leimbach as approximately 50 per cent. A recent experiment made to indicate roughly the order of magnitude of these losses gave as a result a loss of approximately 50 per cent to within ± 10 per cent. From the measured losses in a platinum lamp when burning in air it would scarcely seem probable, notwithstanding the distinct characteristics of the two filaments, that the losses in the Nernst should be as low as 5 per cent or 10 per cent.

Due to the pronounced negative temperature coefficient for the material of the glower at ordinary temperature, it is necessary to place in series with the glower a ballast resistance. The magnitude of this temperature coefficient is evidenced by the fact that for a 110-volt, 44-watt lamp the resistance of the glower which is 320 ohms at normal voltage (110 volts), drops to 240 ohms at 125 volts, and rises to 600 ohms at 92 volts.[56] The necessary ballast, for which is chosen a material with high-positive temperature coefficient, must have a resistance such that at normal burning 10 per cent of the supplied energy is lost in the ballast. There is another known loss of 2 per cent, which arises from the necessity of a magnetic cut-out to throw the heating coil out of circuit when the glower begins to conduct.[57]

The question of losses is intimately connected with that of the explanation of the efficiency [58] of the Nernst, for which values ranging from 2.0 to 3.0 watts per mean spherical candle have been given. It is probable that the average value lies between 2.4 and 2.8 watts per mean spherical candle corresponding to 4 or 5 lumens per applied watt. If there is any large loss of energy by conduction or convection, this efficiency could only result from moderately high temperature or markedly selective emission. The estimates of temperature [59] that have been given range from 1800° Abs., made from extrapolated thermo-couple measurements, to 2450° Abs., determined by optical methods. It is quite probable that the true temperature is at least above 2000° Abs., and hence several hundred degrees higher than that of the incandescent mantle.

To what extent selective emission determines the efficiency is not known. In the discussion of the mantle it was seen that the rare-earth oxides frequently exhibit selectivity to the extent of pronounced bands, particularly at low temperatures and in a finely divided condition. Such a banded spectrum has been observed for the Nernst glower, both in the visible and infra-red regions at abnormally low temperatures, but the bands disappear at higher temperatures so that in the neighborhood of the temperature of normal operation the spectrum is practically continuous. At this temperature, if there is any selective emission, at least in the visible spectrum, it is of the nature of that found for metals, being merely an exaggerated relative emission in the shorter wave-lengths, as compared with the radiation of a *black body* at the same temperature.

Various estimates have been made of the ratio $\left(\frac{L}{R}\right)$ of the energy radiated per second in the visible spectrum to the total emission per second.[60] Ingersoll, using Ångström's method, obtained for a 110-volt, 89-watt glower, 0.046; Drude quotes a value of 0.065 for a glower at 1 watt per hefner, which perhaps corresponds to a slightly higher temperature than normal operation. Coblentz, by integration of an energy curve obtained 0.055 for a filament at 83 watts (presumably 88 watts normal). It is probable that $\frac{L}{R}=0.05$ expresses approximately the relative amount of energy radiated in the visible spectrum between $\lambda=0.38\,\mu$ and $\lambda=0.76\,\mu$. Without a knowledge of the losses in the glower it is impossible to compute the ratio $\frac{L}{Q}$ of the energy radiated in the visible spectrum

per second to the power supplied to the lamp. If we assume the conduction and convection losses to be 50 per cent, as indicated by the experiment to which reference was made, then $\frac{R}{Q}=0.50$, and hence $\frac{L}{Q}=\frac{L}{R}\times\frac{R}{Q}=0.025$. On the basis of the same assumption, in conjunction with the average value of 2.6 watts of power supplied per mean spherical candle, or 4.8 lumens per watt, in a normal lamp, we obtain the value of $\frac{\phi}{R}$, the ratio of luminous flux to total energy radiated as about 9.6 lumens per watt, which would be obtained from a *black body* at 2200°-2300° Abs. From this it would seem that the temperature of the Nernst is either quite high or else that there is selective emission to partly account for the efficiency.

The same result can be arrived at from Drysdale's[a] value of the so-called mechanical equivalent $\left(\frac{\phi}{L}\right)$ for the Nernst, which is 150 lumens per watt. Taking $\frac{L}{R}=0.05$, as given above, it follows that $\frac{\phi}{R}=\frac{\phi}{L}\times\frac{L}{R}=150\times0.05=7.5$ lumens per watt radiated. Indeed, the extension of this method leads indirectly to the energy emission in the Nernst. For, if the efficiency is 7.5 lumens per watt radiated $\left(\frac{\phi}{R}\right)$, and 4.8 lumens per watt supplied $\left(\frac{\phi}{Q}\right)$ it would follow that $\frac{R}{Q}=0.64$, and so the loss $(Q-R)$ is approximately 36 per cent of the power supplied.

7. *The Physics of the Fire-Fly and Other Light-Producing Organisms*

Although the fire-fly can scarcely be considered as a commercial illuminant, its interest and the attention which it has received merits its brief consideration here. It is peculiarly fitting that this natural illuminant should be discussed at the end of the series of human attempts at light production because, from the standpoint of radiant efficiency, it surpasses any other known source. In the first lecture we found that if all the energy supplied to a lamp were radiated, and if all the radiant energy lay at that wave-

length in the visible spectrum to which the average human eye is most sensitive, the highest possible efficiency would be obtained.

In the fire-fly we have practically an exemplification of at least one of these requirements.[a] According to the best information at present it would appear as though, from the standpoint of radiation, the efficiency of the fire-fly is almost as great (estimated at 96-97 per cent) as that of the most efficient radiator possible. Unfortunately, we do not know what chemical and biological transformations occur in the process of "glowing," and without this knowledge we can form no idea of the real efficiency of transformation.

The process of light production in the fire-fly is called luminescence, and seems to depend on the presence of oxygen and water. Other living organisms, such as glow worms, certain bacteria and numerous fishes, exhibit the property of light production, but our knowledge of these at present is quite meager. Further investigation of these natural lamps may disclose processes of light production which could with profit be copied by man in the construction of artificial sources.

8. The Distribution of Energy in the Spectra of the Various Luminous Sources

One of the most interesting of the physical characteristics of luminous sources is the distribution of energy in their spectra. The spectral distribution determines the ratio $\left(\frac{L}{R}\right)$ of the energy radiated per second in the visible to that radiated per second in the complete spectrum, and also the ratio $\left(\frac{\phi}{L}\right)$ giving the photometric value of the visible radiant energy. Eliminating conduction, convection and other incidental losses, the energy distribution determines the commercial efficiency of practical sources, accounts for the quality of the composite light, and explains the appearance of colored objects illuminated by it. We are interested to know whether the spectrum of a source is continuous, discontinuous or banded; what proportion of the energy is in the visible spectrum, and whether in cases of continuous spectra the distribution is that of *black-body* radiation at some temperature or distinctly different from it owing to pronounced selectivity.

It is ordinarily considered that gases and liquids when incan-

descent emit discontinuous spectra, but that solids in general emit continuous spectra in which the energy is distributed very much the same as in the spectrum of a *black body*. But even for luminous gases and vapors certain distinctions must be made in the light of recent experiment and theory. The bright-line spectrum, as in the spectrum of sodium when common salt is heated in a Bunsen flame, has generally been considered as intimately connected with some chemical reaction, in the course of which the sodium atoms are brought into a radiating state, which cannot be reproduced by mere heating of sodium vapor. When gases or vapors are heated, it has usually been agreed that only banded spectra are obtained, except when the temperature is so high, as in the quartz-mercury arc, that there is a continuous spectrum as background to the bright lines. The bright lines are obtained only when chemical or electrical excitation is employed, and not when the gas or vapor is merely heated. Some recent experiments by Bauer seem to indicate an exception to this rule that bright-line spectra are always associated with so-called luminescence, but this work is too recent to justify a reversal of opinion in this regard at the present time.[a]

For solids which radiate approximately as a *black body* the luminous efficiency increases rapidly with the temperature, and it is to the temperature influenced to some extent probably in all cases, and to a very considerable extent in some cases by selectivity in the emission, that the luminous efficiency of many sources is to be ascribed. There is a class of solids, however, illustrated by the rare-earth oxides of the incandescent mantle and the Nernst glower which, though solid, exhibit at least at low temperatures, peculiar banded spectra superimposed upon a continuous background.

It is perhaps not appropriate to discuss in these lectures theories of spectral energy distribution, however attractive such a comparative discussion might seem in the light of the varied spectral phenomena exhibited by the different commercial light sources. The presentation of the spectra of all the sources in one section, however, does not contemplate such a discussion, but is intended rather to give a better comparative idea.

In Figure 6 are plotted the spectral energy curves in the visible region for various common light sources. These curves show the absolute distribution of energy for each source, but not the absolute amount of energy radiated per unit area, being plotted in arbitrary units so chosen that the ordinate at $\lambda = 0.59\,\mu$ is the same for all.

The curves were taken from the best published values[64] in most cases, but were partly determined by the author to fill in gaps in the literature of the subject. The variations in the curves obtained by different observers for some of the sources were found to be strikingly large, owing partly to the conditions of the experiment

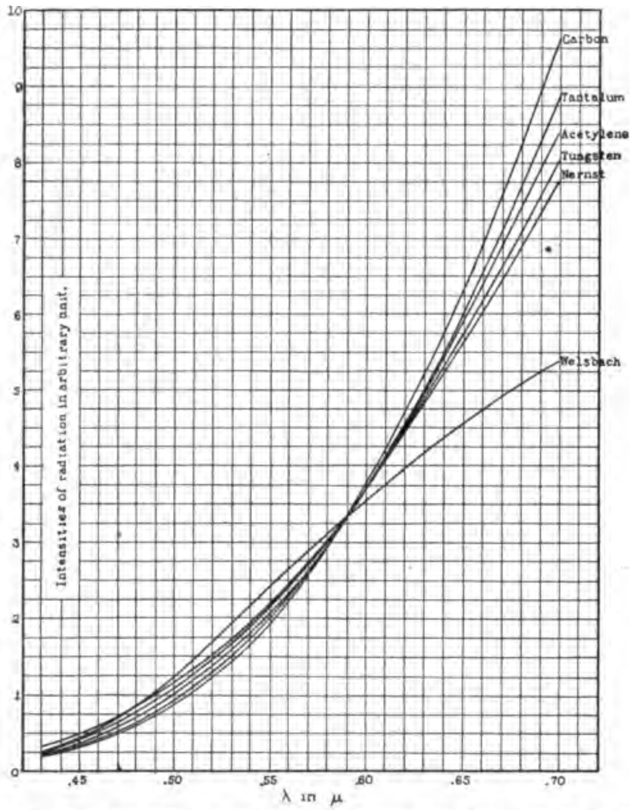

FIG. 6.—Energy Curves for Different Sources in the Visible Spectrum.

and partly to variations in the exact nature of the illuminant. In such cases what seemed to be the best average value was taken.

Spectral energy curves in the visible spectrum are given for the following light sources: ordinary carbon lamp at 3.1 watts per mean horizontal candle, tantalum lamp at 2 watts per mean horizontal candle, and tungsten lamp at 1.25 watts per mean horizontal candle; Welsbach regular commercial upright mantle (average of

various specimens), Nernst glower (average of various types), and acetylene (average of various determinations with different burners, and under different conditions). In every case the spectrum is continuous. But, although the spectra are continuous, the distribution is not in every case that which could be obtained from a *black body* at the proper temperature. Thus the incandescent mantle shows evidence of a pronounced selectivity in the green.

The spectrum of an incandescent mantle depends greatly on the composition of the mantle and on the temperature to which it is heated in the Bunsen flame, which latter depends on the heating value and composition of the gas used, and on the adjustment of the flame. The spectrum of acetylene depends on the burner and on the thickness of the flame, containing relatively more blue in the thin than in the thicker flames. It also depends to some extent on atmospheric conditions. Hence, the curves given for these sources, the incandescent mantle and acetylene, can only be considered as representative of the general type of curve obtained. Indeed, investigators frequently fail to give the exact specifications of the sources employed, making accurate comparisons impossible. It would seem as though, despite the immense amount of work done on commercial light sources, there is still lacking a comprehensive comparative study of the exact spectral compositions of these sources under carefully defined conditions.

It was hoped that a curve for the open arc might be included, but when the literature was searched for data on the energy distribution in the visible spectrum of the arc, very few curves were found, and these showed such enormous discrepancies that no value could be attached to a mean curve derived from them. The curve is continuous in the visible spectrum with a superimposed band in the blue due to the arc flame.

The spectra of the Moore tube, the mercury arc and the various luminous and flaming arcs have not been given in Figure 6 because their spectra are discontinuous, consisting mainly of distinct bright lines, which it would be difficult to represent to scale of intensity. For such sources the most important facts for us to know are (1) how closely the bright lines occur, and (2) the integral color of the light, i. e., the color which a white surface would assume when illuminated by the light. These questions will be discussed subsequently in considering the quality of the light from the various sources as determined by the use of the colorimeter.

Comparable in importance with the spectral energy distribution in the visible spectrum, that in the infra-red region demands our consideration.[65] In fact it is the relative amount of energy in the visible as compared with that in the infra-red, taken together with the distribution in the visible spectrum, which determines the candle-power for each watt radiated. The difficulties in the way of making accurate infra-red measurements are in some ways greater than those encountered in the visible spectrum, which no doubt explains the paucity of available data on infra-red energy curves. Coblentz gives as the infra-red curve for a tungsten lamp, pre-

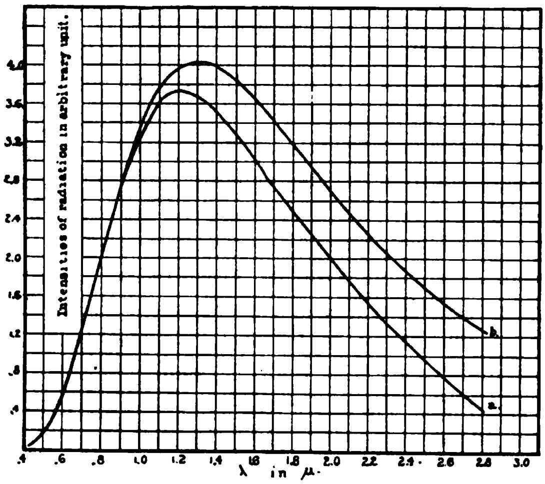

FIG. 7.—a. Energy Curve for Tungsten Lamp at Normal Voltage. b. Energy Curve for a *Black Body* at 2200° Abs.

sumably under normal conditions, that shown in Figure 7, curve "a." In general form it resembles the energy curves of a *black body*, but differs somewhat from the latter. Thus, if we plotted the energy curves of a *black body* at such a temperature that the distribution in the visible spectrum was the same as that of the tungsten, the two curves would differ in the infra-red, that of the tungsten lying below that of the *black body*. Such a *black-body* curve is given in curve "b," corresponding to a *black body* at 2200° Abs., at which temperature the *black body* has approximately the same distribution of energy in the visible spectrum as the tungsten lamp at normal efficiency. The two curves are plotted

to the same ordinate at the same wave-length of the visible spectrum, say $\lambda=0.7\ \mu$.

For the electric incandescent lamps at normal operation, curves somewhat similar to that of tungsten would be found. For carbon the curve would correspond more nearly to that of a *black body*, but the temperature of the *black body* for the same spectral distribution in the visible would be lower than that for tungsten. For osmium probably the greatest deviation from the *black body* would be found.

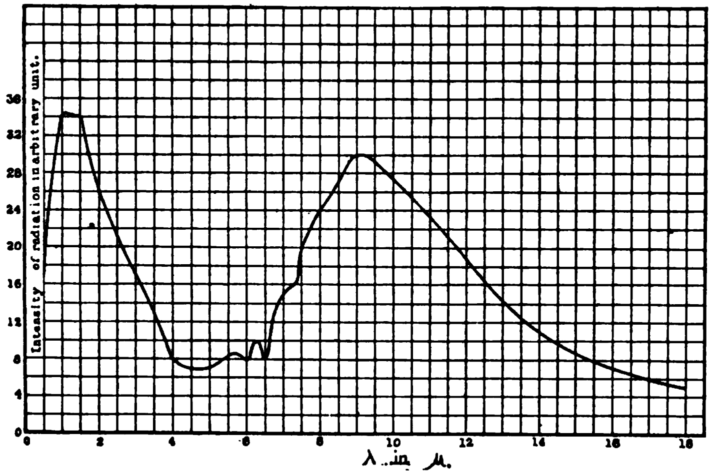

FIG. 8.—Energy Distribution for a Welsbach Mantle—According to Rubens.

The infra-red curve for an incandescent mantle (composition 99.2 per cent thoria, 0.8 per cent ceria) has been found by Rubens, by subtracting the radiation of the open Bunsen burner from the combined radiation of the burner and mantle. This curve is given in Figure 8. The peculiar broken form of the curve seems to be characteristic of the radiation from rare earths at moderate temperatures. The curve for the Nernst found by Coblentz (Figure 9) is quite smooth, although the glower, like the incandescent mantle, is composed of rare-earth oxides. But at lower temperatures the Nernst glower also shows evidence of a banded spectrum. Whether, in the case of the Nernst at normal operation, the smoothness is to be ascribed entirely to a higher temperature than the mantle, or to its more compact form, remains to be determined.

In Figure 10 is given the infra-red curve of acetylene as found by Stewart. For the same reasons as those given for omitting the visible spectra of the various flaming and luminous arcs and vacuum-tube lamps, as the Moore tube, no attempt will be made to give here the infra-red energy curves of these sources.

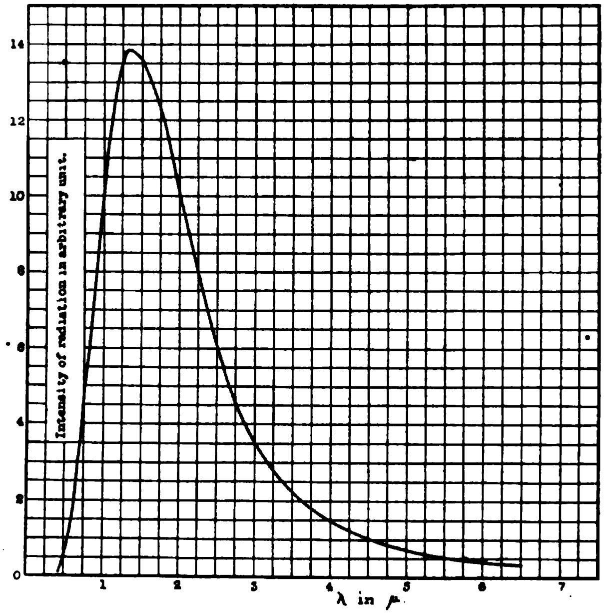

Fig. 9.—Energy Distribution of a 110-Volt Nernst Glower Operated at 77.7 Watts—According to Coblentz.

9. The Quality of the Light from the Various Luminous Sources

Closely associated with the question of spectral energy distribution is that practical one of the quality of the light from illuminants and the appearance of colored objects when illuminated by these illuminants, as explained at length in the first lecture. When the energy distribution in the visible spectrum is continuous and represented by a smooth curve, the integral color of a source, i. e., the color which a white surface illuminated by it assumes, is a fair indication of the variation in color values which will occur when the source is substituted for average daylight, taken as normal white light. But if the spectrum of an illuminant is discontinuous,

composed of a number of distinct lines, the distribution of these lines, together with the integral color, must be examined.

The integral color of the light from any source can readily be measured by determining the relative amounts of red, green and blue light which when mixed give a resultant color which matches in hue that from the source under investigation. Such measure-

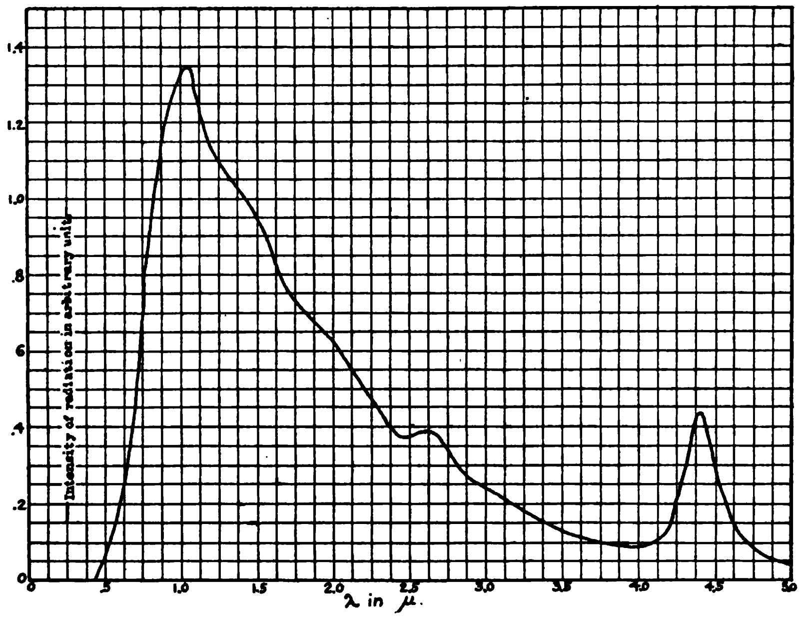

FIG. 10.—Energy Distribution for Acetylene Flame—According to G. W. Stewart.

ments carried out with the F. E. Ives colorimeter have been published by H. E. Ives [66] for a number of illuminants. These results are given in Table II. White light is taken as that emitted by a *black body* at 5000° Abs., for which the sensation values are red 33.3 per cent, green 33.3 per cent and blue 33.3 per cent. The color values of the various illuminants are expressed in terms of red, green and blue sensations, such that the three values given add up to 100 per cent.

From a consideration of this table it is seen that the carbon-dioxide vacuum tube approaches most nearly to average daylight.

Although the spectrum of the vacuum-tube source is always discontinuous, the number of bright lines in the spectrum of carbon dioxide is very large, and the lines are distributed throughout the entire visible spectrum, being thus equivalent for practical purposes to a continuous spectrum. The other sources which show discontinuous spectra, as stated in the discussion of spectral energy distributions, are the low-pressure mercury arc and the ordinary luminous and flaming arcs. In the case of the mercury arc the effect of the visible spectrum being composed of a few lines widely separated is plainly shown in the unnatural appearance of certain colored objects illuminated by its light.

One significant feature in regard to the integral color of light sources is the relatively different impressions produced by two lights, each slightly different from average daylight, when the direction of the difference is one way or another. If the color of a light is approximately that which a *black body* gives at some temperature, it does not appear nearly so strikingly different from daylight, although the hue may be distinctly reddish, as a light which differs from daylight in such a way as not to lie on the scale of color which a *black body* assumes as the temperature is varied. The explanation of this phenomenon comes rather within the province of physiological optics than that of physics.

TABLE II

CLASSIFICATION OF LIGHT SOURCES ACCORDING TO COLOR VALUES

Source.	Sensation values.		
	Red.	Green.	Blue.
1. Black body at 5000° Abs.	33.3%	33.3%	33.3%
2. Blue sky	32.0	32.2	35.8
3. Overcast sky	34.6	33.9	31.5
4. Afternoon sun	37.7	37.3	25.0
5. Hefner	55.0	38.8	6.2
6. 3.1 w. p. c. carbon lamp	51.3	40.4	8.3
7. Acetylene	49.1	40.5	10.5
8. Tungsten, 1.25 w. p. c.	48.7	40.5	10.9
9. Nernst	49.2	40.7	11.1
10. Welsbach, ¼% ceria	42.5	40.8	16.7
11. Welsbach, ¾% ceria	45.5	42.0	12.5
12. Welsbach, 1¼% ceria	47.2	41.8	11.0
13. Direct current arc	41.0	36.3	22.7
14. Mercury arc	29.0	30.3	40.7
15. Yellow flame arc	52.0	37.5	10.5
16. Moore carbon dioxide tube	31.3	31.0	37.7

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III

THE CHEMISTRY OF LUMINOUS SOURCES

By Willis R. Whitney

CONTENTS

Introduction.
Peculiar position of the element carbon in almost all lighting systems.
    Carbon heated to luminescence in oil, illuminating gas and acetylene flame.
    Arc lighting and incandescent lighting.
Substitution of other materials for luminous carbon in flames.
    Drummond light.
    Welsbach mantle.
Carbon arc lighting—History of.
    Electrochemistry of the arc.
    Combustion and electrical migration.
    Enclosed arc and air control.
    Direct and alternating current arcs.
    Arcs of other material than carbon.
    Solids heated by arc.
Non-carbon arcs.
    Iron, magnetite, titanium carbide arcs.
Efficiency and size of light unit.
The mercury arc.
    Its ultra-violet light and production of ozone.
Vacuum tube lighting.
The incandescent lamp.
    Carbon filament.
        Chemistry of the methods of manufacture.
        Forming, baking, firing, coating and metallizing.
    Osmium filament.
    Tantalum filament.
    Tungsten filament.

Only a few years ago anyone studying the chemistry proper of the sources of artificial illumination might well have been led to conclude that he could confine his efforts to a single element, i. e., carbon. This was owing to its general and peculiar applicability in all types of artificial lighting, no matter how widely they differed in their methods of employment of this interesting element. I even

think he might have been forgiven for assuming that in relation to light carbon occupied some such particular place among the elements, as it does in the chemical relations of life. Carbon, of all the elements, is the basis of organic chemistry and the one fundamental element without which organic substance and life itself are impossible. All artificial light was at that time due to carbon heated to incandescence. The efficiency of the light sources depended on the efficiency of maintaining carbon at a high temperature. In the various types of oil lamps which were in use several thousand years ago, the light is due to the incandescence of carbon. This carbon is a product of decomposition of the vapors of the oil. It can easily be deposited from the flame and be kept from burning by introducing a cooled surface into the flame. This service of the carbon is a double one in the case of oil and ordinary gas illumination. Here an element is needed which forms readily vaporizable compounds or gases, and compounds, too, which are decomposed by the moderate heat produced by the reaction of the compound with the air, and, finally, the element must itself be non-vaporizable at the temperature of the continuing reaction. In these respects carbon is apparently the only element which possesses the needed properties. It did not follow of necessity that this same element should be best suited for electric arc lights and for incandescent filaments, and yet for half a century it was the mainstay for both methods of illumination. Possibly it is this apparent selective fitness of carbon among the 77 elements that caused postponement of attempts at discovery of other methods of illumination.

In an address of this kind on the chemistry of luminous sources (a subject selected to properly fit into a comprehensive scheme covering illuminating engineering), it seems best to spare special emphasis of selected kinds as much as possible, and to consider in something of a co-ordinating way the chemistry of all the practical methods of lighting.

In such a consideration one is soon impressed with the fact that the several different types of illumination differ relatively little in their net efficiency. The labor and material involved in the production of the light of a candle does not seem to differ much by whatever methods one employs to produce the light. A candle-power from a modern oil lamp, an alcohol lamp, from a gas lamp, or from an electric lamp is, speaking quite generally, a matter of about the same order of magnitude of cost. This would not

be so remarkable if they were all nearly perfect illuminants, or if they were all of very high degree of energy efficiency—i. e., if they were all nearly perfect—but they are not.

That they are nearly alike in cost is due to the fact that they are all so far removed from the perfect artificial illuminant that the large proportion of wasted energy practically determines the cost. The kerosene oil lamp uses a few tenths of 1 per cent of the energy of the combustion of the oil in the production of visible light waves. The temperature at which the carbon is heated in this flame is so low that almost any other way of heating the carbon will give more light. In the case of the very intense acetylene flame we probably see the effect of much higher temperature of the carbon particles, as this is a hotter flame than that produced by common gas. It is known that the luminous radiation rises exceedingly rapidly with rise of temperature at burning temperatures, so that the carbon does not have to be heated very much hotter in order to give off a very much greater light. Probably the range of temperature within which carbon is heated in the various kinds of lamps, excepting the arc and acetylene flame, lies below 1800° C.

When ordinary illuminating gas is used, the maximum light is gained by a selected composition of the gas and construction of the burner.

This is almost equal to saying that the gas is so mixed with the air which combines with it that none of the carbon produced by decomposition of the gas is allowed to escape as soot, but is, on the other hand, kept heated without combustion within the flame as long and at as high a temperature as possible. If more air were introduced into the flame, less light would be produced, but a locally higher temperature. This is due to the increased rapidity of combustion of the carbon. This fact led to the introduction of other materials than carbon into the flame to be heated by the burning gas. Naturally, very little advance was made along this line until a scheme for making total and rapid combustion of the gas was developed. This was the work of Bunsen, who found that air mixed with the gas in suitable proportions brought about the effect of raising the temperature of the gas flame. In this application the carbon is immediately consumed and does not lend any luminosity to the flame. The industry waited at least a decade for some suitable substitute for the luminous carbon. It was the

exhaustive work of Dr. Auer von Welsbach which produced the mantles of metallic oxides which we know to-day. These, when heated to the high temperature produced by the combustion of mixed air and gas, give a much greater light for a given rate of gas supply than the previous method of use of the same gas. This increased light efficiency is also greatly augmented by the proper selection of the components of the mantle mixture. It would, at first thought, seem probable that any white mantle capable of withstanding the high temperature of the flame would give the same definite, constant quantity of light under the same conditions of heating gas flame. That this is not so is readily shown by a study of the efficiency of various oxide mixtures when used as mantle compounds. There are a number of metallic oxides which do not melt or vaporize at the temperature of the flame, but the most refractory is not the most satisfactory. Each mixture of oxides seems to have its own characteristic light-giving power, and to possess also some considerable selective power in producing color differences.

This has led to an immense quantity of purely experimental research, in order to discover what particular compound or mixture would give the most efficient and satisfactory light. As an illustration of this fact, it is worth noting that Welsbach discovered that pure thorium oxide, when used in a mantle, will not give a tenth of the light that will be produced under the same conditions by a mantle made of a mixture of 99 parts of thorium oxide and 1 part of cerium oxide. This very interesting phenomenon will doubtless be taken up by Mr. Whitaker, and is therefore only referred to at this point. An instructive article on this subject was published in the April, 1909, number of the *Journal of Industrial and Engineering Chemistry*. It is the one discovery which has apparently given the illuminating-gas industry the help it needed to keep in competition with methods of electric lighting.

Just as no story of incandescent electric lighting can be properly started without at least a reference to the enormous contribution of Edison, so also any history of arc lighting properly commences with Sir Humphry Davy. In 1809 he was experimenting with phenomena produced by a battery of 2000 primary cells, and publicly showed that a very luminous arc was produced when the current passed across the gas between carbon points. While he may not have been the discoverer of the arc, he was one of the first to

see a use for it. For a great many years thereafter no practical application was made of this discovery, because there had not been developed any satisfactory devices for generating the large amount of electrical energy consumed by even a small carbon arc. In 1870 the Gramme generator was devised. Carbon arc lamps were operated from this machine, in place of batteries. Some of the first attempts at practical use of these machines and lamps were made in connection with light-houses on the English and French coasts. Soon thereafter the Jablochkoff electric candle came into use. This is an arc lamp with parallel carbons. These were kept separated by a thin wall of clay, or a mixture of sand and glass, which gradually vaporized during the burning of the arc. At one time several thousand of these were in use in Europe. At the Paris Exhibition, in 1878, the illumination produced by these candles, operated by Gramme machines, marked an epoch in lighting which the previous 30 years of laboratory experiment with arcs had but dimly foreshadowed.

Somewhat later the simple carbon arc was commercially realized, and the clay part of Jablochkoff candles disappeared from the electric lamp for a time.

The phenomenon of this direct-current carbon arc is still quite far from being perfectly understood. From the chemical standpoint, the arc presents two pure carbon pencils, each of which is slowly consumed. In the ordinary lamp the consumption of the positive, which is usually the upper electrode, is much more rapid than that of the lower or negative electrode. It was long evident that the wasting away of the carbon electrodes was largely due to simple combustion by the air, and many attempts were made to prevent this combustion, while retaining the characteristics of the carbon arc. This led to the discovery that the upper electrode is heated much hotter than the lower during the passage of the current, that carbon actually distills from this positive electrode, and when this carbon cannot burn it will deposit upon the cooler parts of the electrode. This property of building out mushroom growths on the electrodes when operated in vacuo or in inert gases seemed to stand in the way of economizing in such a lamp by practically separating the ordinary combustion of the electrodes from the proper electric-arc phenomena. It was finally found, however, that by properly controlling the current and voltage, and by admitting only a very small quantity of air to the globe of a carbon arc lamp,

the combustion of the electrodes could be greatly reduced. This air rate, which is controlled by the openings in the supports of the inner globe of the enclosed arc lamp, so greatly reduces the burning of the electrodes that the life is increased ten-fold or more. This gives us, then, the two primary types of carbon arc lamps, the open and enclosed. In the closed, as in the open, it is the positive electrode which wastes or burns away the more rapidly of the two; it is the hotter and is the source of most of the light from the arc. In the pure carbon arc only a few per cent of the light is due to the flame or arc proper. This arc stream is far from dense, and most of the carbon in the space is already present as carbon monoxide.

While it is out of place here to go very deeply into the conceptions of theories which have been formed to cover the action in the arc, it may not be amiss to point out that the simplest ideas are not applicable. For example, it is quite apparent that a motion of positively charged particles across the gap of the arc does not account for all the phenomena. As will be seen more clearly later, the negative electrode, at least in most cases, is the one which determines the character of the arc, and a carbon arc is still a carbon arc when the positive electrode is some other conducting substance, while it is usually no longer a characteristic carbon arc when the negative electrode is another substance. There is no simple quantitative relation known between the current carried in an arc and the waste or loss at either electrode. In this respect the arc differs from the passage of current through a gap within a solution, for example. Attempts made to determine the minimum loss of electrode for a given arc current have only led thus far to the conclusion that if any quantitative consumption of electrode takes place of necessity when an arc is passing, the quantity of material corresponding to a given current is at least a thousand times smaller than migrates when equal current passes through a solution or an electrolyte. Moreover, it seems that this motion within the arc is usually, if not always, made up of material from the negative electrode. This general subject has led to a great deal of quantitative work in which arc electrodes of other materials than carbon have been used. In most cases, as with carbon, the results are affected by the simultaneous oxidation of the electrodes. Copper and iron electrodes, when used as arc terminals, show such irregularities that it has been impossible to accurately

determine values of loss at cathode or anode which might correspond in some way to the Faraday equivalents in electrolysis. Even when such arcs are operated in inert atmosphere or under water, one usually finds that the material of either electrode has passed in some irregular degree to the other electrode and deposited upon it. Such effects may be largely accredited to simple distillation. Some cases have, however, been found in which the processes of combustion may be fairly well separated from those of current action, and here again it seems proven that in an arc it is essential that material pass from the cathode into the arc space only, and that a consumption of the anode or positive electrode is always an accidental accompanying effect. This will be referred to later.

We have thus far considered only the chemistry of the pure carbon arc. Modification of this arc of interest to illuminating engineers have been many. It seems necessary to refer briefly to a few of them before considering other arcs. The direct-current carbon arc owes its efficiency to the highly heated crater or arc terminal on the positive carbon. When an alternating-current carbon lamp was measured, it was found that not quite so great efficiency was possible, though by the alternating position of the crater with each change in current direction, the distribution of the light is somewhat improved.

Many inventors have attempted to increase the light from a given arc energy by introduction of suitable chemical compounds into the arc. Some of these have led to successful commercial lamps. If a small piece of a very refractory material, such as zirconia, be brought into the carbon arc, it is heated to a temperature at which it is very luminous. This is quite like the use of a rod of lime in the Drummond gas lamp. The difficulties in the way of stability, of mechanism, ignition and control, may account for the failure to develop this device in its simplest form.

A small zirconia rod placed between the two carbon electrodes (when arranged as ordinarily, one above the other), although patented as an arc lamp, has not been commercially developed. A modification of this scheme, whereby a special form of Welsbach mantle is placed about the carbon arc to be heated by the arc, has also not advanced very far. A considerable difficulty in such schemes lies in the fact that the hot path of the arc stream is usually of very small cross-section, and in lamps of moderate energy consumption is not easily confined to a limited position, so that it is not

easy to keep interposed material heated to incandescence by this means.

Countless schemes for continuously introducing powders or vapors into the arc have also been tried. It was found many years ago that the addition of such salts as carbonate of soda to carbon-arc electrodes gave added luminosity to the arc, reduced the voltage across the arc and also permitted the arc to be lengthened without extinguishing it. Very small quantities of such salts are effective. This general knowledge did not produce the modern flame arcs at once, as the effect of such salts as were used a quarter of a century ago was probably not greatly marked or appreciated. About 10 years ago inventions involving this principle became quite common. Perhaps best known among them are those of Blondel in France and Bremer in Germany. They and others made use of very considerable proportions of salts added to the carbon during the manufacture of the electrode. Usually 10 per cent or more of mineral substance was added, and many different salts were proposed. Most successful seem to be the fluorides and chlorides of calcium and magnesium. Some inventors found they were able to construct an operative electrode by using a homogeneous rod of carbon and the salts. Others preferred to confine the salt to a core inside one or both electrodes. In most cases this core also contained some special form of carbon, and in some cases there were two concentric cylinders of various composition about the central core. It has been quite common to use carbon electrodes with a core of soft carbon, as the arc by this means is kept centered on the electrode. The present so-called carbon flame arcs, which are usually characterized by great luminosity, with predominance of reddish-yellow color, are made in the above way. The electrodes usually contain so much mineral matter that they cannot be used in enclosed lamps of the ordinary types. The mineral matter, after passing into the arc, must be carried from the lamp by a good draught, otherwise it will deposit on the globe and soon greatly reduce the luminosity of the lamp. The necessary draught involves also the rapid consumption of the electrodes, so that such lamps usually have to be trimmed or supplied with new electrodes daily. The presence of the salts insures low voltage for the lamp, so that they are usually burned two in series on the 110-volt circuit.

The most useful future application of chemistry to this type of flame arc lamp will doubtless be along the lines of producing as

great an efficiency in white light as is now produced in the reddish tint. Taken as an electric-light source alone, these reddish-flame arcs are the most efficient of any of the commercial lamps. I attach a table of efficiencies of various kinds of electric lamps for comparison. Such a table, taken alone, may be very misleading. No indication of color, convenience, size of unit, and other practical considerations, appear in such a table.

				W.P.C.	
Carbon (open arc)	D.C.	10 A.	43 V.	1.43	(spherical)
" (enclosed)	D.C.	5 A.	80 V.	2.27	"
" (enclosed)	A.C.	7.5 A.	80 V.	2.47	"
Carbon flame arc	D.C.	10 A.	45 V.	.42	"
Magnetite arc	D.C.	4 A.	80 V.	1.25	"
Tantalum	D.C.	.5	110 V.	1.7	(horizontal)
Metallized carbon		.5	110 V.	2.6	"
Carbon		.5	110 V.	3.1	"
Mercury	D.C.	3.5		.6	"
" (pressure)	D.C.			.3	"
Moore tubes	A.C.			1.6	"
Nernst	Both	.25		1.7	"
Osmium	"	.5		1.7	"
Tungsten				1.25	"

It is particularly in the arcs that the chemical nature of the electrodes plays a determining part. When a simple carbon arc is considered, the quality of the carbon is of the greatest importance. Pure graphite is not acceptable, but a hard, dense carbon, quite low in ash and of very fine physical structure, is most satisfactory. For many years these were imported from Germany, and they still are to some extent.

In the introduction of new substances to the carbon arc there are many chemical and physical properties which unite to determine the value of the added substance. The salts of many elements add more or less intense colors to the arc, in accord with the spectrum lines of the particular element. This effect is greatly influenced by the degree of volatility of the salt and by the nature of the other elements or compounds vaporizing at the same time. Calcium oxide does not greatly affect the luminosity of the carbon-arc stream, while calcium fluoride does.

During the past 10 years some advances have been made in the practical use of other arcs than carbon. The best known are the magnetite and the mercury arcs.

The magnetite differs chemically from the carbon in being much less combustible, as it burns only in changing from Fe_3O_4 to Fe_2O_3, in giving non-volatile oxides and in giving to the arc flame, to a high degree of intensity, the characteristic colors of the iron spectrum. The iron spectrum is one of those metal spectra which, while made up of defined lines, contain such a great number of them (over 2000 have been mapped) that the effect is practically that of a continuous spectrum. In the magnetite arc practically all of the light is due to the arc or flame. The luminous positive of the carbon arc is in this lamp replaced by a large block of copper or other metal, which does not contribute to the consumption in the arc, so that this lamp is an arc lamp with only a single consuming electrode. The quality of the arc is greatly influenced by the quality of the magnetite electrode. It might seem probable at first that iron itself would be preferable to magnetite, but long series of experiments seemed to show that a compound and rather complex mixture, containing large proportions of pure magnetite, gave the best results. Such arcs must burn steadily and the electrode must contain a small amount of relatively volatile matter, such as the common salts of potash or soda. For a given current the rate of waste of the electrode can be very materially altered by the addition of otherwise inactive materials, such as alumina and chromium oxide, without any considerable reduction in the light produced. This effect is probably due to the reduction of vapor pressure of the iron oxide in the molten top of the electrode. This corresponds to vapor-pressure reduction in case of simple solutions. Finally, it was found that the intensity of the arc is greatly increased by the addition of another element which has its own rich spectrum, such as titanium. So that the magnetite arc is really the arc spectra of iron and titanium superposed. Such strictly arc flames have one advantage over carbon arcs, in that they can operate economically in small units. The efficiency of the carbon arc is greater the larger the unit within a wide range, but units below 500 watts begin to be relatively inefficient. On the other hand, the efficiency of the strictly luminous arcs is maintained high as low as 250 or 300 watts. This, to the illuminating engineer, means that he has greater elasticity in the distribution of his lighting energy.

The mercury arc may be said to differ but little from the other arcs. It is greatly lengthened by being confined to a glass tube, and thus any combustion or loss of material is obviated. Its color

and light are determined as in the case of other arcs, by the nature of its cathode electrode. The anode, as in the other arcs, may be made of almost any conducting material. The vapors which are produced at the cathode condense to liquid state and return by gravity to the cathode. If the chemical elements had more fluid members among those of highly luminous spectra, the principle of the enclosed mercury lamp would probably quickly yield more new and useful lighting methods. The light of the mercury lamp, when broken down by the prism, is seen to be composed of only a few widely separated lines. Among them is no red. For this reason red articles appear black under this light, and, for this reason, many other colors fail to appear natural under the mercury arc.

There are two interesting facts concerning the mercury arc which may well ultimately be utilized in a practical manner. The arc is very rich in ultra-violet light. This is not particularly noticeable when the arc is surrounded by glass, but when pure quartz is substituted for the glass the ultra-violet light penetrates into the surrounding air. This produces ozone in a very marked manner, and this unfiltered light has a very serious and injurious effect on the eyes. It is highly probable that this modified mercury lamp is to be the most readily applicable form of ultra-violet light for therapeutic purposes. Secondly, it has been discovered that when the arc is operated under two or three atmospheres of mercury pressure the efficiency is high and the color more nearly approaches daylight. Glass tubes will not withstand the temperature of the arc at this pressure, but quartz will. Such quartz mercury lamps are being made and sold abroad at the present time.

Any considerable practical improvement in the color of the mercury arc has not been made by the amalgamation of other elements with the mercury. An element like copper or iron fails to vaporize from the cathode of the mercury arc. Some of the alkali metals somewhat alter the light, but most of them also attack the glass of the lamp. It is worthy of note that some fluorescent dies, rhodamine, for example, are capable of absorbing the green and blue spectral lines and returning in their place some considerable red, but this has not proven an efficient process.

The luminosity of gases and vapors has always seemed a very promising field of artificial illumination. In the case of heated solids, the laws of radiation, convection and conduction are well enough known, so that a field in which less is known is apt to seem

promising. The Geissler or Plücker tubes, in which attenuated gases are rendered luminous by relatively high voltage and low-current discharge, are well known to all. It seems very probable that future developments of importance will be made, and already, in the McFarlane-Moore System, very considerable advances have been made. Here the chemical composition of the gases and their pressure are the determining factors of the color and efficiency. A peculiar phenomenon in these lamps is the apparent consumption of the gas or air in the tubes. Gradually, in such apparatus, the gas disappears, as though driven into or combined with the glass. For this reason the inventor of this system has devised an automatic inlet valve which operates to let gas into the lamp when the vacuum rises to a certain degree. This seems to be a similar effect to the well-known "hardening" of X-ray bulbs from continued use, which is an improvement in vacuum, and is also noted in the case of the vacuum of an ordinary incandescent lamp.

Without wishing to go deeply into the history of the incandescent lamp, it is necessary to point a moment to the work of Mr. Edison. The fact that electric current flowing through a conductor could heat it to incandescence had long been known. That carbon in filament form, when preserved from combustion by a vacuum, would make a lamp was clear. J. W. Starr had patented such a lamp in 1845, and Swan, in England, had exhibited one in 1879. But between this point and a satisfactory incandescent lamp was a great gulf, which needed the untiring energies of such an inventor as Mr. Edison to help bridge. A piece of carbonized thread, confined in such a vacuum as was known when he undertook the work, did not constitute a practical lamp at all. In the poor vacuum produced by methods used in those days, even a good filament of the present time would have produced but a very imperfect lamp. The simpler methods of producing carbon filaments are capable of yielding only very imperfect lamp filaments. There are few artificial products which excel the filament in the divergence between apparent simplicity and actual complexity.

The choice of elements for incandescent-lamp filaments may be said to be more nearly a physical than a chemical problem, but in the manufacture of all of them chemistry plays a dominant rôle. The best carbon filaments now in use may be described as consisting of a core of pure carbon, not graphite, covered with a coat or shell of pure graphite, which has been so changed by an electric-

furnace treatment, under atmospheric pressure, that it has a positive-resistance temperature coefficient instead of a negative one. This graphite coating, to which the name metallized graphite has been given, has the appearance of having been melted or sintered together, and thus differs from all other graphite.

The chemical and physical processes by which these carbon filaments are produced are as follows:

High-grade cotton is dissolved in a strong solution of zinc chloride, which is then squirted through a small hole into dilute alcohol. The alcohol coagulates the viscous solution of cellulose so that a transparent thread is the product, and by washing this in running water the zinc chloride is removed.

Another equally satisfactory method for reaching the same end is to squirt a thick solution of nitro-cellulose, dissolved in acetic acid, into a container holding water. Washing with ammonia sulphide and water changes the nitro-cellulose into non-explosive hydro-cellulose. This product is then dried in the air while stretched on drums. It is then cut to desired lengths, formed into the necessary loops on brass frames, and finally packed in graphite boxes in a packing material such as baked peat, and very gradually heated until carbonization takes place. In this process the carbonized filaments are heated to as high a temperature as can be obtained by gas or oil-heated muffles.

The product at this point is dense, hard carbon, which, even under the microscope, is far from having the appearance of charcoal, and seems almost free of pores. The carbon filament in this form would make a very inferior lamp. The color or quality of its surface, and probably the volatility of its material, is not nearly so favorable to lamp making as the corresponding properties of graphite. At any definite operating energy the amount of light produced by a gray-graphite surface is greater than that produced by a black-carbon surface, so that the carbon filaments are graphite-coated. This is done by heating them by the current in an atmosphere of hydro-carbon, such as benzine, at low pressure. The quality and thickness of the coat may be controlled by the duration and temperature of the treatment. Until a few years ago the greater part of all carbon filaments were made in this way. It was then found that the effect of subjecting the graphite-coated filaments to temperatures above 3000° C. for a few minutes changed the graphite very materially in its properties. Those which are of interest to

us now are the resistance, its temperature coefficient and the stability at operating lamp temperatures. Briefly, the resistance of the graphite coat is reduced to about 20 per cent of its original resistance. Its temperature coefficient is reversed and its lasting powers in the lamp increased nearly three-fold.

This point seems a proper one at which to mention the standard of use for incandescent lamps as determined by practical conditions. Burning at a low efficiency, an incandescent lamp has practically an indefinite life. At 3 watts per candle-power it may have 1200 hours' life and at 2.5 about 500 hours to 80 per cent of its original candle-power. It has been found by use that about 500 hours' life for a carbon lamp is most practical, this 500 hours being the length of time the lamp remains above 80 per cent of its starting candle-power. The metallized filament lamps, therefore, instead of being burned at the former efficiency of 3.1 watts per candle, are made to burn at about 2½ w. p. c., at which they have about 500 hours' life. Evidently the higher the cost of the lamp the more stress has to be laid upon long life, while with very cheap lamps there is an advantage gained by burning them at unusually high efficiency and replacing them at the end of much less than 500 hours.

The history of the development of the various metallic filament lamps is particularly interesting from the chemical standpoint. In the early days of incandescent lighting Mr. Edison and others recognized the peculiar value of metallic filaments because of their flexibility and electrical conductivity. At that time platinum and iridium were the metals which offered most promise. They were the metals of highest melting point, so far as then known. It was soon apparent that these metals could not be run at high enough temperature to make a practical lamp, though they were very nearly suitable. Mr. Edison then carried out a great number of experiments in an attempt to raise the melting point of the platinum. The effect of the occluded gases was carefully studied, but a commercial lamp did not result. For over a quarter of a century thereafter, it remained unknown that at least six or seven of the then known metals had higher melting points than platinum. The entering wedge into this field was driven by Dr. Auer von Welsbach, who had acquired a personal and almost exclusive knowledge of a large group of more or less rare chemical elements in connection with his extensive researches, which were crowned by his gas-mantle inventions. At this time probably none of the metals which melt

higher than platinum had ever been produced in any other form than that of a fine black powder. Osmium was the first of a trio of metals to become a nearly practical filament. It occurs in nature in metallic state, usually alloyed with iridium, platinum, rhodium and ruthenium. It is found only as very small grains or plates, and nowhere in any considerable quantity. By mixing powdered metallic osmium with a suitable starch or sugar binder, Welsbach squirted a thread which, after drying and baking, could be freed of carbon by heating in a mixed atmosphere of hydrogen and water-vapor. The resulting metallic filament was quite soft when hot, but was well suited for incandescent lamps, as it withstood temperatures necessary to produce a lamp burning satisfactorily at about 1½ watts per candle-power. The world's known supply of osmium is very small, and to conserve this supply the lamps were usually rented instead of being sold.

In 1901 Dr. Werner von Bolton announced the discovery of ductile tantalum. Operating in an incandescent lamp, it could be burned at about 1.7 watts per candle-power for a thousand or more hours. The metals tantalum and niobium are a pair usually occurring together and formerly quite difficult of separation. They occur in small quantities in Connecticut, in the Black Hills of Dakota, in Sweden and in Australia, the mineral being usually tantalite (a compound of the oxides of tantalum and iron, with or without manganese or tin) or some combination of tantalum and niobium oxides with iron, etc., as columbite, samarskite, fergusonite, etc. It was necessary first to perfect methods of preparing the pure metals, and of these the tantalum was found to have the higher melting point. It is about 3100°, while that of niobium is about 2900°, or still well above platinum.

Until this investigation it had apparently been known only as powder. This powder was melted together into large buttons in an electric arc and then drawn to wire in the usual manner through diamond dies.

Probably most, if not all, of the tungsten filaments in the lamps on the market are made by some method of squirting through a die tungsten powder mixed with a binding agent. The metal, in finely divided state, is usually obtained by the reduction of tungstic oxide at a red heat by hydrogen. This oxide is in turn obtained from the minerals Wolframite, which is a tungstate of iron or iron and manganese, and Scheelite, a tungstate of calcium. Several

thousand tons of ore, averaging over 50 per cent tungstic oxide, are mined annually, largely for use in high-speed tool steel.

Some of the successful processes for making the filaments are as follows:

The powdered metal is mixed with a proper carbonaceous binder, then formed into threads by being forced through a suitable die, dried and baked at about red heat. They are then heated by passage of current through them in a suitable atmosphere of hydrogen or mixture of hydrogen and nitrogen. By this treatment a shrinkage of the filament takes place, it becomes dense and metallic in appearance, and at the same time the carbon present is removed. The product is, therefore, pure tungsten.

Similarly, a metallic binding agent may be used. The finely divided metal in one such process is mixed with a cadmium-bismuth amalgam and the resulting mixture is pressed through a die. A thread not unlike a fine, lead fuse wire is the result. On heating this in in vacuo all metals but the tungsten are vaporized, and at the final temperature this is also sintered together into a compact filament.

In the case of tantalum, nature seems to supply just about enough of the ore to satisfy the demand, and probably this element would have been a more successful competitor in the incandescent-lamp field if it only had to contend against carbon and osmium. It was more efficient than the former and much more plentiful than the latter. It is interesting to recognize the fact that the most recent successful metal filament, tungsten, occurs in nature in abundance. It was discovered by Scheele in 1781. For over 200 years it was known in the pure state only as an infusible gray and heavy metallic powder. Its melting point, as determined by Pirani, is 3350°, and is the highest melting point of which we have measurement. The only measurement of higher temperature on the earth is that of the carbon-arc crater, said to be about 3500° C., by Burgess and Waidner. In all types of incandescent lamps there lies a promise that continued study will give continued advance in the art. This is sought usually as higher efficiency. A carbon lamp will burn a few moments at an efficiency 10 times as great as its normal value. In other words, from the materials at hand, this increase in efficiency is possible for a short time. It seems, therefore, not impossible that this limiting time feature may be better controlled when better understood.

IV

ELECTRIC ILLUMINANTS

By Charles Proteus Steinmetz

CONTENTS

General

1. The different forms of radiators and different kinds of radiation. Classification of electric illuminants.
2. Importance of the volt-ampere characteristic and the resistance-temperature characteristic of the conductor used in electric illuminants. Discussion of the multiple or constant potential, and the series or constant-current electric distribution system.

Solid Conductors

3. Volt-ampere and resistance-temperature characteristic of incandescent lamp filaments. Positive and negative temperature coefficients, $\frac{de}{di} > 0$. Stability of operation on constant potential and on constant current circuits. [Fig. 1: Volt-ampere characteristics of incandescent lamp filaments. Fig. 2: Resistance-characteristics of incandescent lamp filaments.]
4. Volt-ampere characteristic of pyroelectrolytic conductors. The Nernst lamp glower as pyroelectrolyte. The instability range, $\frac{de}{di} < 0$, of pyroelectrolytes on constant potential supply, and the necessity of steadying resistance or reactance. The Nernst lamp. [Fig. 3: Volt-ampere characteristic of low resistance pyroelectrolyte.]
5. The light radiation of solid conductors, as incandescent lamps and the Nernst lamp glower. Black-body, gray-body and colored-body radiation. Effect on the efficiency of the incandescent lamp filament and the Nernst lamp glower. Limitation of efficiency.
6. Relation of refractoriness and vapor tension or disintegration, to the possible efficiency of the incandescent lamp. Comparison of the carbon filament with the metal filaments.
7. The production of the carbon filament lamp. Base carbon and treated carbon, and their stability.
8. Metallized carbon, its resistance and temperature coefficient, and the gem lamp.
9. Metal-filament incandescent lamps. Osmium lamp, tantalum lamp, tungsten lamp. Their efficiencies.

10. The manufacture of the tungsten lamp.
11. Thinness and length of metal filaments. Fragility.
12. Efficiencies of the different incandescent lamps. Conventional rating in horizontal candle-power. Relation of efficiency to useful life.
13. Relation of the efficiency of the incandescent lamp to the size of the unit, or the power consumption. Limitation by supply voltage at small units, by size of the lamp globe at large units. Wide range of units with fairly uniform efficiency.
14. Inferiority of the incandescent lamp in efficiency, to the flame arc and luminous arc. Superiority in small units. Main field of application of incandescent lamps and Nernst lamps in small units, where no other electric illuminant exists.

GASEOUS CONDUCTORS

15. Difference between disruptive or Geissler-tube conduction, and continuous or arc conduction.

GEISSLER-TUBE CONDUCTION

16. Electric characteristics of Geissler-tube conduction: total voltage, terminal drop and stream voltage as function of gas pressure. [Fig. 4: Volt-pressure characteristic of Geissler tube with air as conductor. Fig. 5: Volt-pressure characteristic of the Geissler tube with mercury vapor as conductor.]
17. Performance, efficiency and color of light. The Moore tube.

ARC CONDUCTION

18. Nature of the arc conductor. The arc as unidirectional conductor. Rectification by the arc. The alternating current arc. Constant-pressure and varying-pressure arcs.
19. Volt-ampere and volt-length characteristics of the arc: $\frac{de}{di} < 0$. [Fig. 6: Volt-ampere characteristic of magnetite arc of .5, 1.5 and 2.5 cm. length. Fig. 7: Volt-length characteristic of magnetite arc at 2, 4, 8 and 16 amperes.]
20. Dependence of the arc voltage on two independent variables, current and arc length. Instablity of the arc on constant voltage supply. Necessity of steadying resistance or reactance. The stability curve of the arc. [Fig. 8: Stability curve of the 1.5 cm. magnetite arc.]
21. Instability of parallel operation of arcs without steadying resistances. Instability due to non-inductive resistance shunt. Extinction by shunted capacity. The arc as interrupter. The singing arc.
22. Stream voltage and terminal drop of the arc. Heating of the terminals by the terminal drop. The carbon arc as incandescent radiator. Relation between the efficiency of the carbon arc, and the size and the life of the terminals.

23. The open carbon arc or short burning arc lamp. The enclosed carbon arc or long burning lamp. Its inferiority in efficiency.
24. Uneconomical operation of continuous-current series arc circuits. The series alternating enclosed arc lamp. Its very low efficiency.
25. Replacement of the enclosed alternating carbon arc by the magnetite arc lamp in street lighting, by the intensified arc or the tungsten incandescent lamp in indoor lighting. The intensified arc lamp.
26. The luminous arc and the flame arc. Their characteristic differences, advantages and disadvantages. The magnetite arc.
27. The flame carbon arc. Relation between size of electrodes and efficiency. The short-burning and the long-burning flame carbon arc. The yellow color of the flame carbon arc. Titanium, calcium and mercury as the three most efficient arc stream radiators.
28. The mechanism of the arc lamp: starting device, feeding device, steadying device, shunt protective device, damping devices. Series lamp, shunt lamp, differential lamp.
29. The effective resistance of the arc. Relation between arc length and efficiency. The short carbon arc and the long luminous and flame arcs.
30. Regulation of arc lamp for constant light flux. The floating system of control of the carbon arc and its advantages. Fixed arc length required by the luminous arc. Its difficulties in constant potential lamps. The compromise control of the flame carbon lamp.
31. Classification of arc lamps; the most important forms of arc lamps:
    - The open carbon arc on 9.6 amperes series direct current circuits.
    - The enclosed carbon arc, for multiple and series circuits, on alternating and on direct current.
    - The intensified carbon arc, on alternating and on direct current circuits.
    - The yellow flame carbon arc, on alternating and on direct current circuits.
    - The magnetite arc.
    - The mercury arc.
32. Increase of the efficiency of the arc with increasing size of the light unit. Relation between the efficiency of the arc lamp and the current, arc length and power, at constant arc length, constant current and constant power. The condition of maximum efficiency. [Fig. 9: Efficiency and power consumption of the 4-ampere magnetite arc for different arc lengths. Fig. 10: Efficiency and power of the .7-inch magnetite arc for different currents. Fig. 11: Efficiency, arc length and voltage of the 300-watt and the 500-watt magnetite arc, for different currents. Fig. 12: Relation between voltage, current, arc length and efficiency of the magnetite arc, under the condition of maximum efficiency, for various powers.]
33. Comparison of the arc lamp and the incandescent lamp.

VACUUM ARCS

34. The low-pressure mercury arc in the glass tube. The high-pressure mercury arc in the quartz tube. Their characteristics.

SENSITIVITY TO VARIATIONS OF THE ELECTRIC POWER SUPPLY

35. Comparison of various forms of incandescent lamps and arc lamps regarding their sensitivity to variations of the electric power supply.

GENERAL

1. The Different Forms of Radiators and Different Kinds of Radiation. Classification of Electric Illuminants

In the production of light from electric power, solids, liquids or gases (the latter including vapors) may be used as conductors of electric power, and the radiation may be due to incandescence of the radiator, that is, temperature radiation (black-body, gray-body or colored-body radiation), or it may be the result of a more or less direct conversion of the electric power into radiation, as luminescence.

Solids as conductors of electric power are used in the various forms of incandescent lamps: the different types of carbon-filament lamps and the metal-filament lamps, as the osmium lamp, the tantalum lamp and the tungsten lamp, and also in the Nernst lamp. Liquids are not used as conductors, due to their difficulty of application, but gases and vapors are extensively used in the various forms of arc lamps, as the open and the enclosed carbon arcs, the flame arcs and the luminous arcs, which latter include the vacuum arcs, and in the Geissler tube as illuminant (Moore light). In the former, the arc lamps, the vapors of the electrode material are used; in the latter, the Moore light, the gas which fills the space between the electrodes.

In all solid conductors, and also in the plain-carbon arc lamp, the light production is due to temperature radiation or incandescence, either black-body or gray-body radiation, or colored-body radiation. In the flame arcs, luminous arcs (including vacuum arcs) and Geissler tubes luminescence plays an essential part in the light production.

2. Importance of the Volt-Ampere Characteristic and the Resistance-Temperature Characteristic of the Conductor Used in Electric Illuminants. Discussion of the Multiple or Constant Potential, and the Series or Constant-Current Electric Distribution Systems

Since in electric illuminants the light is given by electric conduction, the properties of the electric conductor, which is used in the illuminant, are of the foremost and fundamental importance, that is, the relation of current and voltage to each other, or the so-called "volt-ampere characteristic" of the conductor; and the relation of the ratio of volts and amperes, that is, the effective resistance, to the temperature, that is, the "resistance characteristic" of the conductor. This is obvious, since the illuminant must be capable of use in the existing electric-power distribution systems.

Electric power is distributed in two different forms: by the constant-potential or multiple-distribution system, that is, at the constant voltage of 110 or 220 volts,* or by the constant-current or series system.

In the constant-potential system all apparatus are connected in parallel between the same supply mains, and thereby receive the same voltage, but each takes a different part of the supply current. All the illuminants must therefore be designed to operate at the same constant-terminal voltage of 110 or 220, and within such variations of this voltage as may be met in a constant-potential distribution system, which varies from 1 per cent to 5 per cent or more, depending on the character of the system. The different illuminants, however, may be designed for different currents. The multiple system has the advantage of permitting practically unlimited extension: with increase of the number of illuminants, the current in the supply feeders and mains increases, and larger conductors become necessary, but the voltage remains the same. When the number of illuminants becomes so large that the size of supply conductors becomes uneconomical, more sources of supply become necessary. Since, however, these sources of supply are usually sec-

* 110 volts here means any constant voltage between about 105 and 125, and 220 volts twice this value: not the same voltage is used in different distributing systems, but slightly different voltages, for the purpose of making the economical production of exactly rated incandescent lamps possible. (See "General Lectures on Electrical Engineering," by the author, p. 12.)

ondary stations, that is, transformers or converters receiving their power from a primary generating system at high voltage, this introduces no serious limitation. The constant-potential system of distribution therefore is now generally used, with the exception of those few cases, where it is not economical: at the low voltage of 110 or 220 volts, the distance to which electric power can be sent is rather limited. When numerous illuminants are scattered over a wide area this difficulty is met by secondary stations, as transformers, as stated above. If, however, individual illuminants are scattered over a wide area, as in street lighting, the individual illuminants cannot be reached from one 110- or 220-volt feeding point, while the installation of a transformer at every lamp is uneconomical, and in this case the constant-potential system becomes uneconomical and the constant-current system is used. For street lighting the series system is therefore universally employed, with the exception of those few places in large cities where the street lamps can be reached by a multiple system installed for general distribution.

In the constant-current or series system all apparatus are connected in series with each other, and thereby receive the same current, and the voltages consumed by the different illuminants add. The illuminants therefore are designed for the same current, but may consume different voltages. Since the voltage of a distribution circuit cannot be indefinitely increased without involving difficulties with insulation and danger to life and fire risks, the number of apparatus which can be connected into one series circuit is rather limited; a series circuit is a very small unit of electric power, from our present point of view, and as economy requires the use of the largest possible units series circuits are used only in those cases where they are economically necessary, that is, for street lighting. It was, however, with series arc circuits that electric lighting started in the early days.

Series circuits are usually operated at 4, 5, 6.6 or 7.5 amperes, some of the old open carbon arc circuits at 9.6 amperes, and with voltages ranging usually from 4000 to 6000.

Not all conductors, and therefore not all illuminants, can be connected promiscuously into multiple circuits or into series circuits, even if designed for the proper voltage respectively current, and the study of the electric characteristics of the conductors which are used in illuminants is therefore of importance for their design and operation.

SOLID CONDUCTORS

3. *Volt-Ampere and Resistance-Temperature Characteristic of Incandescent Lamp Filaments. Positive and Negative Temperature Coefficients, $\frac{de}{di} > 0$. Stability of Operation on Constant-Potential and on Constant-Current Circuits*

The conductors of incandescent lamps are ohmic resistances, that is, conductors in which the resistance does not directly depend on current or voltage, but is constant at constant temperature, and if it varies with a change of temperature, in case of a negative temperature coefficient, that is, a decrease of resistance with increase of temperature, the decrease of resistance with increase of temperature is less than the increase of current required to cause the increase of temperature. That is, such conductors are characterized by the relation:

$$\frac{de}{di} > 0.$$

In other words, an increase of current always causes an increase of terminal voltage. If the resistance were perfectly constant, that is, the temperature coefficient zero, the voltage would be proportional to the current, and the volt-ampere characteristic given by a straight line going through the origin, I in Fig. 1, and the resistance characteristic given by a horizontal straight line, I in Fig. 2. No conductor exists which has zero temperature coefficient over more than a limited range of temperature.

If the temperature coefficient is positive the resistance increases with increase of temperature, and the voltage thus increases more than proportional to the current; that is, an increase of current i causes an increase of temperature and thereby of resistance r, and thus an increase of the voltage $e = ir$, which is greater than proportional to i, as shown in curves II to IV in Figs. 1 and 2. Inversely, if the temperature coefficient is negative the resistance decreases with increase of current, and therefore of temperature; but the voltage still increases with increase of current, though less than proportional to the current, as shown in curves V and VI in Figs. 1 and 2.

As illustrations are shown in Fig. 1 the volt-ampere characteristic, and in Fig. 2 the resistance characteristic of the conductors or filaments of various types of incandescent lamps. In Fig. 1

the co-ordinates have been chosen so as to start all curves at the slope of 45° at the origin. In Fig. 2 the co-ordinates have been chosen so as to give 10 at the operating point of the lamp. In

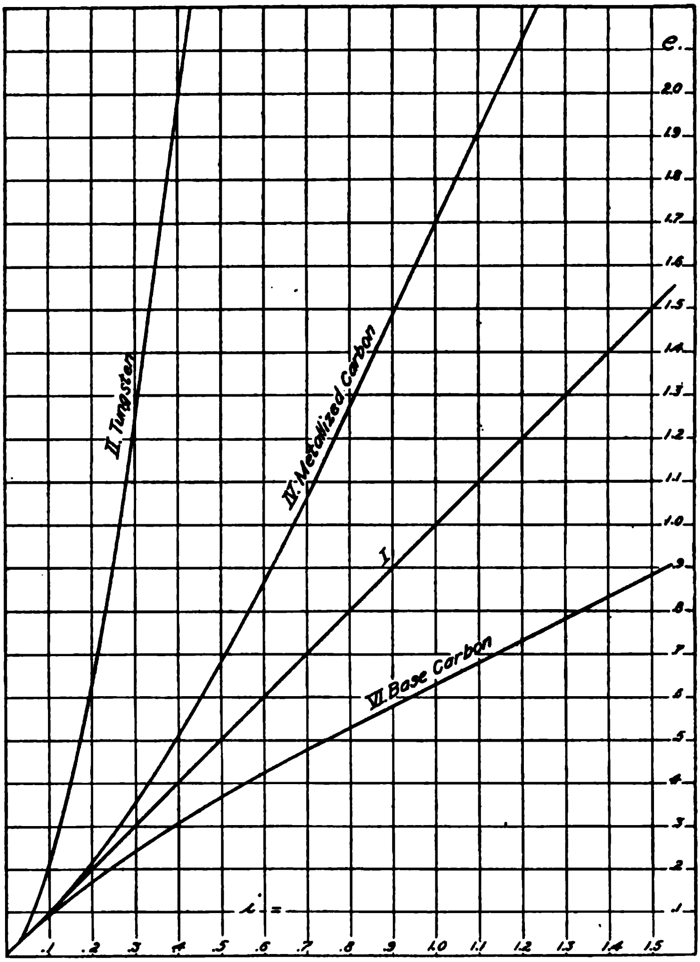

FIG. 1.—Volt-Ampere Characteristics of Incandescent Lamp Filaments.

Fig. 2 as abscissae have been used $\sqrt[4]{w}$, which with a black-body radiator would be proportional to the absolute temperature (for high values of w). It is:

I. The theoretical conductor of constant resistance.

II. The tungsten lamp filament.

III. The osmium lamp filament.
IV. The metallized carbon, or gem lamp filament.
V. The treated carbon, or 3.1-watt carbon-filament lamp.
VI. The untreated carbon, or base filament.

Such a conductor, which fulfils the conditions, $\frac{de}{di} > 0$, can be

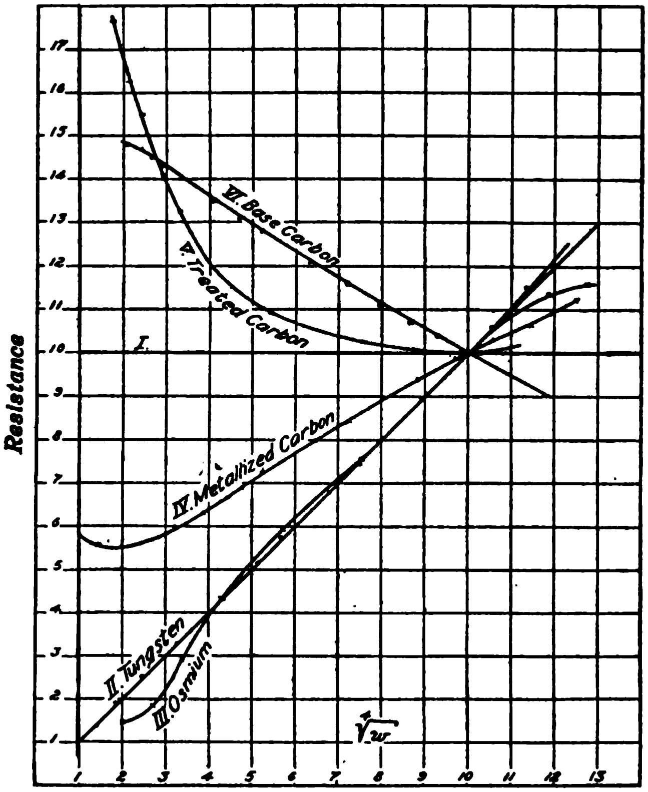

FIG. 2.—Resistance-Temperature Characteristics of Incandescent Lamp Filaments.

operated satisfactorily on constant-potential as well as on constant-current circuits, provided, obviously, that its resistance is chosen so as to consume the rated power at the constant voltage respectively current of the circuit; on constant-potential supply the current, and thereby the power consumed by the conductor, is limited to

that corresponding to the supply voltage; on constant-current supply the terminal voltage, and thus the power consumed by the conductor, is limited to that corresponding to the supply current.

4. Volt-Ampere Characteristic of Pyroelectrolytic Conductors. The Nernst Lamp Glower as Pyroelectrolyte. The Instability range, $\frac{de}{di} < 0$, of Pyroelectrolytes on Constant-Potential Supply, and the Necessity of Steadying Resistance or Reactance. The Nernst Lamp

Very different are the conditions in the conductor of the Nernst lamp, the Nernst lamp glower. This belongs to a class of conductors, the *pyroelectrolytes,* in which the temperature coefficient within a certain range of temperature, and thus of current, is so greatly negative, that with increase of current the terminal voltage decreases. That is, with increase of temperature the resistance drops faster than the increase of current required to produce the increase of temperature, and the voltage $e = ir$ thus decreases with increase of i. In this range, it therefore is:

$$\frac{de}{di} < 0.$$

Such pyroelectrolytic conductors are many metal oxides, silicates, sulphides, etc. A typical volt-ampere characteristic of such a conductor (magnetite) is given in Fig. 3, with $\sqrt{i}$ as abscissae,* the terminal voltage e as ordinates. As seen, from $i = 0$ to i_1, it is $\frac{de}{di} > 0$; from i_1 to i_2 it is $\frac{de}{di} < 0$, and for $i > i_2$ it is again $\frac{de}{di} > 0$. With most pyroelectrolytes the voltage peak at i_1 is so high that the conductor cannot be carried beyond it by the mere application of voltage, but artificial heating is required, and the resistance below i_1 is usually extremely high, usually near i_2 fusion occurs, and beyond that the conductor is an ordinary electrolytic conductor.†

The operating point of the Nernst glower is in the range between i_1 and i_2, where $\frac{de}{di} < 0$.

* For the purpose of better showing the initial part of the curve, $\sqrt{i}$ is used as abscissae, instead of i.

† See "Electric Conduction," paper read before the Electrochemical Society, 1907, by the author.

A conductor, in which $\frac{de}{di} < 0$, can be operated on constant-current supply, but cannot be operated on constant-voltage supply; but at constant terminal voltage it is unstable within the entire range from i_1 to i_2, in Fig. 3; on constant-voltage supply an increase of current, by lowering the voltage consumed by the conductor, causes a further increase of current and power, and thus further decrease of voltage, increase of current and power, etc.,

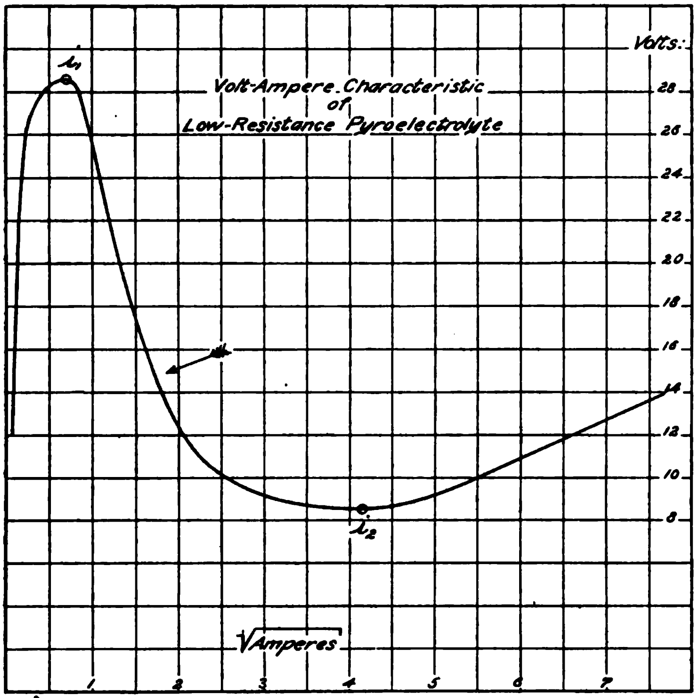

FIG. 3.

and the conductor destroys itself by melting; a slight decrease of current causes an increase of the voltage required by the conductor, and since this is not available on constant-voltage supply a still further decrease of current, increase of required voltage, etc., and the conductor open-circuits, that is, the lamp goes out. On constant-potential supply, such a conductor therefore either open-circuits or short-circuits, and to operate it at constant power on a multiple circuit a resistance or reactance is required in series

5

to the pyroelectrolyte sufficiently large so that the voltage consumed by pyroelectrolyte (glower) plus steadying resistance increases with increase of current, that is, fulfils the conditions of operation on constant-potential supply, $\frac{de}{di} > 0$.

The Nernst lamp thus requires a "steadying resistance" in series to the glower. To reduce this resistance, and thereby the waste of power caused by it, to a minimum, iron wire is used, operated in hydrogen or in a vacuum at that range of temperature at which the temperature coefficient of the iron is abnormally high, and with increase of the current i the resistance r very rapidly increases, thus causing an abnormally rapid increase of ir.

In arc- and Geissler-tube conduction, a similar instability on constant potential will be discussed.

5. *The Light Radiation of Solid Conductors, as Incandescent Lamps and the Nernst Glower. Black-Body, Gray-Body and Colored-Body Radiation. Effect on the Efficiency of the Incandescent Lamp Filaments and the Nernst Glower. Limitation of Efficiency*

The light production by solid conductors as radiators is temperature radiation. That is, by the resistance of the conductor, the electric power i^2r is converted into heat, causing a rise of temperature which produces the radiation.

Normal-temperature radiation, that is, black-body or gray-body radiation, as given very closely by the various types of carbon-filament lamps, is a very inefficient light producer. The efficiency of light production increases with increase of temperature, but is still very low at the highest temperatures at which solids can be operated. The selective radiation of a colored body which is deficient in radiating power in the ultra-red gives a higher efficiency of light production. The radiation of some of the metal filaments, and that of the Nernst lamp glower, is such a colored-body radiation, and thereby gives a light efficiency higher than corresponds to the temperature of the radiator. However, the selectivity seems to decrease with increase of temperature, that is, with increasing temperature the body seems to approach more a gray body. For instance the Nernst glower radiates strongly selective at low temperature, at its operating temperature the radiation curve has

greatly smoothed out,* and while there is probably a gain in efficiency in some metal filaments and the Nernst glower over normal-temperature radiation, the gain does not seem to be so large as to bring the efficiency of light production much beyond that reached by normal-temperature radiation, and it does not appear probable that we shall be able to reach very much higher efficiencies by colored-body temperature radiation.†

6. Relation of Refractoriness and Vapor Tension or Disintegration to the Possible Efficiency of the Incandescent Lamp. Comparison of the Carbon Filaments with the Metal Filaments.

Since temperature radiation reaches fair values of light efficiency only at very high temperatures, only the most refractory bodies come into consideration as radiators in incandescent lamps.

The most refractory substances are carbon, tungsten, osmium, tantalum, etc.‡

However, refractoriness is not the only requirement, but the vapor tension, or rate of disintegration of the material below the melting point, is equally of importance, since on it depends how far we can, in the operating temperature of the radiator, approach its melting point. This is well illustrated by the relation between tungsten and the different forms of carbon.§

Carbon is the most refractory body, and has been the first employed in commercially successful incandescent lamps, and the carbon-filament lamp still is the one used in the largest quantities. Carbon has the disadvantage of a relatively rapid evaporation or disintegration far below its boiling point, and this limits the operating temperature of the carbon filament so that we cannot get the full benefit of the high refractoriness of carbon; but metals, as tungsten, which are less refractory than carbon, can give a higher efficiency by being operated at higher temperature. Great differences in stability, however, exist between different modifications of carbon.

* Bulletins of the National Bureau of Standards.

† See "Radiation, Light and Illumination," by the author, p 70.

‡ See "Radiation, Light and Illumination," p. 77.

§ See "Radiation, Light and Illumination," p. 79.

7. *The Production of the Carbon-Filament Lamp. Base Carbon and Treated Carbon, and their Stability*

The first commercial carbon-filament incandescent lamps were made of carbonized bamboo fiber. Very soon this was replaced by the squirted filament, which could be produced more uniformly. A solution of cellulose in zinc chloride (or cupric ammon), or of nitro-cellulose in glacial acetic acid, is squirted through a fine hole into a hardening solution: methyl alcohol with zinc-chloride solution, diluted acid with cupric-ammon solution, water with nitro-cellulose. The filament is then washed, put into the desired shape (in the case of nitro-cellulose, after reduction to cellulose) and dried. It then consists of a structureless cellulose, in appearance very similar to horn. This is now carbonized in a gas furnace at high temperature, and constitutes what is now known as a "base filament," because it is mainly used as a base on which to deposit a better form of carbon. The base carbon is not very stable at high temperature, and early lamps made of it, therefore, had only a relatively low efficiency. It has a high resistance and a high negative-temperature coefficient, as shown by its characteristic in Figs. 1 and 2. Somewhat later a considerable improvement in efficiency resulted from the introduction of the "treated filament." The base filament is electrically heated in an atmosphere of hydrocarbon vapor (gasolene) in a vacuum, and by the dissociation of the vapor a shell of a different modification of carbon is deposited on the base. This shell carbon has a far greater stability at high temperature, thereby allowing the operation of the lamp at higher temperature and thus higher efficiency. It is of lower resistance, and in the treated filament lamp most of the current thus flows in the shell; less in the inner core or base of the filament. The temperature coefficient of the shell carbon is still negative, but decreases with increasing temperature, and finally begins to rise, so that the compound structure of the treated filament gives a characteristic as shown in Fig. 2.

8. *Metallized Carbon, its Resistance and Temperature Coefficient, and the Gem Lamp*

A few years ago a further advance was made by discovering a form of carbon of still much higher stability, the metallized carbon used in the so-called "gem lamp." The shell carbon (but not

the base carbon) converts at the highest temperature of the electric furnace into a modification of carbon of nearly metallic character; it has a very low resistance, lower than some metals, and a positive-temperature coefficient, like metals, though lower than that of pure metals, as shown by the characteristic of the carbon filament with metallized shell, in Figs. 1 and 2. In the production of the gem lamp the base filament is heated in the electric furnace to expel all impurities, then treated in gasolene vapor, and thereby a layer of shell carbon deposited on it, and then is once more heated in the electric furnace. The filaments are then sealed in glass bulbs with platinum leading-in wires and exhausted. It gives an efficiency of about 3.3 watts per candle-power.

Apparently, the electric resistance and its temperature coefficient are indications of the stability of carbon at high temperature; the lower the cold resistance and the higher its temperature coefficient the more stable is the carbon at high temperature, and the higher efficiencies can thus be reached.

9. Metal-Filament Incandescent Lamps. Osmium Lamp, Tantalum Lamp, Tungsten Lamp. Their Efficiencies

In recent years metal-filament incandescent lamps have been developed, and are rapidly replacing the carbon-filament lamps by their higher efficiency.

First, the osmium-filament lamp was developed, giving an efficiency of about 1.9 watts per candle-power. Its filament was made by some squirting process, similar to the carbon filament. It found a limited use only, since osmium is a very rare metal, existing in very limited quantities, and was soon replaced by the tantalum filament. Tantalum is a ductile metal, and the tantalum lamp is made by winding drawn tantalum wire on a glass frame. The tantalum lamp gives an efficiency of about 2.6 watts per candle-power, hence lower than the osmium lamp but higher than the gem lamp. Tantalum, while a rare metal, exists in fairly large quantities, and the tantalum lamp appeared very promising until the development of the more efficient tungsten lamp of 1.5 to 1.7 watts per candle-power.

The tantalum lamp was the first incandescent lamp made of drawn metal, and showed the features of a much better life with direct current than with alternating current; with alternating cur-

[illegible] the drawn filament loses its ductility and gradually offsets, that is, breaks up into numerous short lengths, which are welded together.

[illegible] The Manufacture of the Tungsten Lamp

The highest efficiencies of incandescent lamps have been realized [illegible] the tungsten filament. Tungsten, or wolfram, is a fairly common metal; [illegible] is extremely refractory, more than osmium or tantalum, [illegible] less than carbon, but fairly difficult to produce in such purity as [illegible] necessary [illegible] filament.* Several methods of manufacture of tungsten filaments have been devised and are still in commercial [illegible], though many millions of tungsten lamps have been [illegible]. [illegible] series of processes consists of squirting the metal as [illegible] state, with some binder, and then burn[illegible] electric heating in a suitable gas; another [illegible] filament of tungsten oxide with some reducing ma[illegible] heat, and then eliminate the excess of reducing [illegible] electrically heating in a suitable gas at [illegible]. A third process consists of squirting or drawing [illegible] tungsten alloy, and by electrically heating evaporate [illegible] and sinter the tungsten, and, finally, methods [illegible] draw the pure tungsten metal into wire of [illegible] for use in filaments. All these methods [illegible] filament which is not ductile, but brittle, like [illegible] filament, and, therefore, due to its ex[illegible] fragile.

[illegible] Metal Filaments. Fragility

[illegible] lower resistance than the base [illegible] the carbon filament, [illegible] at the same supply voltage [illegible] light flux, they must be of ex[illegible] length. Therefore, in these lamps [illegible] used in series, or with drawn [illegible] wound zigzag on a frame. [illegible] the metallized carbon filament;

* [illegible] by 1.3 per cent of carbon would rep[illegible] tungsten carbide W_2C.

while the metallized carbon also has a very low resistance, it is used only as a thin shell on the base carbon, which practically does not carry any current, in the gem lamp, while the metal filaments are solid conductors in which the whole cross-section conducts.

12. Efficiencies of the Different Incandescent Lamps. Conventional Rating in Horizontal Candle-Power. Relation of Efficiency to Useful Life

The approximate efficiencies, or rather specific consumptions, of the different types of incandescent lamps are:

Base carbon filament (not used any more)	5 watts per c. p.
Treated carbon filament	4
Metallized carbon (gem filament)	3.3
Tantalum lamp	2.6
Osmium lamp	1.9
Tungsten lamp	1.5 to 1.7*

Light flux is measured in lumens, and light efficiency thus in lumens per watt, specific consumption in watts per lumen. Usually instead of the lumen as measure of the light output of an illuminant the mean spherical candle-power is used, which is $\frac{1}{4\pi}$ times as much, and the efficiency then given in mean spherical candles per watt, the specific consumption in watts per mean spherical candle.

By convention, incandescent lamps are usually rated in mean horizontal candles, and their specific consumption expressed by giving the watts per mean horizontal candles and the spherical reduction factor. Thus, above lamps are commercially rated at:

Treated carbon filament	3.1 watts per mean horizontal candle-power
Gem lamp	2.6 watts per mean horizontal candle-power
Tantalum lamp	2.0 watts per mean horizontal candle-power
Osmium lamp	1.5 watts per mean horizontal candle-power
Tungsten lamp	1.15 to 1.33 watts per mean horizontal candle-power

At the spherical reduction factor 0.78, this gives above values. In comparison with other illuminants, obviously, the horizontal candle-power has no meaning, but the total flux of light, that is, the mean spherical candle-power, has to be used.

* See "Radiation, Light and Illumination," p. 179.

When considering efficiency, however, the useful life of the lamp must also be considered. Obviously, higher or lower efficiencies may be reached by operating the same lamp at higher or at lower voltage.

When speaking of the efficiency of a carbon-filament lamp it is understood, by general convention, that the lamp is operated at such a voltage as to give a useful life of 500 hours. As useful life is understood the time during which the lamp, on constant-voltage supply, decreases by 20 per cent in candle-power.*

With metal filaments no such convention has yet been generally established, but due to the higher efficiency and higher cost of the lamp probably a useful life of 1000 hours or more will be economical.†

Efficiency tests of incandescent lamps therefore are meaningless if not accompanied by life tests at that efficiency.

13. Relation of the Efficiency of the Incandescent Lamp to the Size of the Unit or the Power Consumption. Limitation by Supply Voltage at Small Units, by Size of the Lamp Globe at Large Units. Wide Range of Units with Fairly Uniform Efficiency

Characteristic of the incandescent lamp is, that its efficiency is (theoretically) independent of the unit of light; filaments of large diameter and great length, consuming large power and giving a large unit of light, give the same efficiency when operating at the same temperature as filaments of small diameter and short length, that is, filaments which consume small power and give small units of light, and operating at the same temperature, should have the same life. Thus incandescent lamps give a wide range of sizes of illuminants of nearly the same efficiency.

A limitation of the possible size of incandescent light units appears with small sizes in the voltage of the system of electric power-supply. At the same supply voltage—110 or 220—a smaller light unit requires a filament of smaller diameter, and finally a point is reached where the small diameter makes the filament so delicate that either the life of the lamp would be materially short-

* See "Radiation, Light and Illumination," p. 79.

† See "General Lectures on Electrical Engineering," by the author, p. 209.

ened, or a lower operating temperature, that is, lower efficiency, must be allowed. Thus, with the carbon-filament lamp on 110-volts supply, 50 watts (or 16 horizontal candle-power with the treated filament, 20 horizontal candle-power with the gem filament), are the smallest units at which full efficiency can be reached. Carbon-filament lamps of less than 50 watts for 110-volt circuits, therefore must be made for lower efficiency, and the efficiency lowered the more the smaller the unit is. Obviously, for a 55-volt circuit, an 8-candle-power lamp could be made of the same efficiency as the 16-candle-power lamp on the 110-volt circuit, and the 220-volt, 16-candle-power lamp cannot be built any more for the same efficiency as the 110-volt lamp, other things being equal.

The same applies still more to metal-filament lamps, as in these the filaments are thinner and longer than in carbon-filament lamps of the same voltage and candle-power. Thus in the tungsten lamps higher efficiencies are given to the larger units.

For low-voltage lamps, obviously, this limitation of minimum size, by the mechanical structure of the filament, does not exist, and lamps of 1- or 2-watts consumption, or even less, at 4- to 10-volts supply, can be made of the same efficiency as the 50-watt lamp.

With increasing size of the unit, a practical limitation is also reached; the useful life of the carbon-filament lamp is limited largely by the blackening of the globe by carbon deposits, and to give equal blackening the surface of the lamp globe should be proportional to the power consumed in the lamp. This, however, gives for large units impracticably large globes, and the use of smaller globes leads to a shorter life.

This limitation exists less with metal-filament lamps. In these it seems that the life is not so much limited by the gradual blackening of the globe as by impairment of the vacuum, and for equal performance only the volume of the globe and not the surface, as with the carbon filament, should increase proportional to the power consumption. This makes metal-filament lamp units of several hundred watts feasible, while carbon-filament lamps of such power consumption are impracticable.

The gem lamp, due to the metallic properties of the filament, stands intermediate between the treated carbon filament and the metal filament in this respect, and lamp units of 250 watts have been fairly successful.

14. Inferiority of the Incandescent Lamp in Efficiency to the Flame Arc and Luminous Arc. Superiority in Small Units. Main Field of Application of Incandescent Lamps and Nernst Lamps in Small Units where no Other Efficient Electric Illuminant Exists

The incandescent lamp thus gives units of light, of practically the same efficiency, from a fraction of a candle-power to several hundred candle-powers, covering a wider range than any other electric illuminant.

However, the efficiency of light production is of lower magnitude than that of some other electric illuminants; even in the most efficient incandescent lamp, the tungsten lamp, the specific consumption of 1.5 to 1.7 watts per candle is of far higher magnitude than the specific consumption reached in some flame arcs and luminous arcs, of half a watt or less per candle-power.

Thus, in efficiency, the incandescent lamp cannot compete with the flame arc or the luminous arc, and is therefore excluded from economical use in those cases where these arcs can be used, but must find its field of application in those cases where the more efficient illuminants cannot be used, and especially is this the case with smaller units of light, since the efficiency of the arc rapidly decreases with decreasing power consumption, while that of the incandescent lamp remains the same, and the incandescent lamp (including the Nernst lamp) is therefore the only one available for smaller units of light, of 100 candle-power or less.

GASEOUS CONDUCTORS

15. Difference between Disruptive- or Geissler-Tube Conduction and Continuous or Arc Conduction

Two forms of conduction of gases or vapors exist: disruptive- or Geissler-tube conduction, and continuous or arc conduction. The distinction is, that in the former the gas which fills the space is the conductor; in the latter conduction takes place by a moving stream of electrode vapor. Gas or vapor conduction is accompanied by luminescence of the conductor, and thus can be used for light production. In Geissler-tube conduction the light gives the spectrum of the gas which fills the space between the electrodes; in arc conduction the spectrum is that of the electrode material.*

* See "Radiation, Light and Illumination," p. 98.

The conductor may be at atmospheric pressure, as in the carbon arcs, flame arcs and most luminous arcs; or in a vacuum, as in the Geissler tube or the vacuum arc (of which the only industrially important exponent is the mercury arc).

GEISSLER-TUBE CONDUCTION

16. Electrical Characteristics of Geissler-Tube Conduction: Total Voltage, Terminal Drop and Stream Voltage as Function of Gas Pressure

Very little is known on the electrical characteristics of Geissler-tube conduction. The only commercial illuminant of this class is the Moore tube.

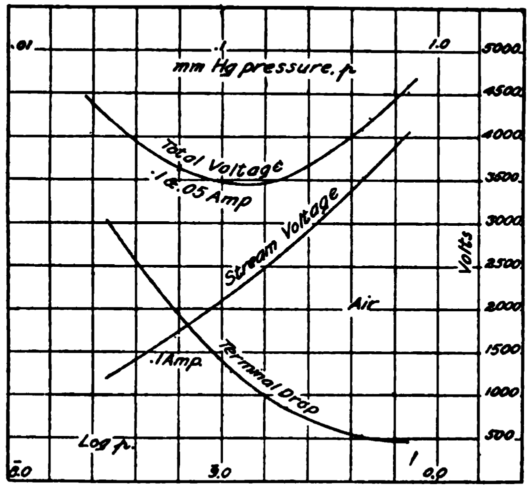

FIG. 4.—Volt-Pressure Characteristic of Geissler Tube.

It seems that, at constant temperature and constant gas pressure, the voltage consumed by the Geissler tube is approximately constant and independent of the current, that is, $\frac{de}{di} = 0$. The volt-ampere characteristic of the Geissler tube thus would be a straight horizontal line. As result hereof, a Geissler tube cannot be operated on constant-supply voltage, but requires a steadying resistance or reactance to fulfil the conditions of stability, $\frac{de}{di} > 0$. The reactance of the step-up transformer is used for this purpose in the Moore tube.

The voltage consumed by the Geissler tube consists of a potential drop at the terminals, the "terminal drop," and a voltage consumed in the luminous stream, the "stream voltage," which latter is proportional to the length of the tube. Both greatly depend on the gas pressure, and vary with varying gas pressure in opposite directions: with increasing gas pressure the terminal drop decreases and the stream voltage increases, and the total voltage consumed by the tube thus gives a minimum at some definite gas pressure. This pressure of minimum total voltage depends on the length of the tube, and the longer the tube is the lower is the gas pressure of minimum total voltage.

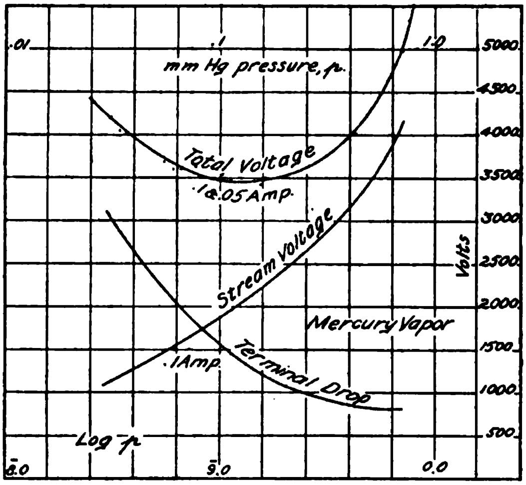

FIG. 5.—Volt-Pressure Characteristic of Geissler Tube.

In Fig. 4 is shown the voltage-pressure characteristic, at constant current of 0.1 and of 0.05 ampere, of a Geissler tube of 1.3 cm. diameter and 200 cm. length, using air as conductor; and in Fig. 5 the characteristic of the same tube with mercury vapor as conductor.* Figs. 4 and 5 also show the two component voltages, the terminal drop and the stream voltage. As abscissae are used the logarithms of the gas pressure, as measured by McLeod gauge at the moment of taking current and voltage readings.

* It is interesting to note, that total voltage, terminal drop and stream voltage in the Geissler tube using mercury vapor as conductor, are nearly the same as with air, and entirely different from the terminal drop and the stream voltage of the vacuum mercury arc. The spectrum is the same, the mercury spectrum.

With increasing pressure the discharge finally stops, due to the limited supply voltage; with decreasing pressure, finally the gas density becomes so low that a tendency to arc conduction appears, and the beginning of arc formation usually destroys the tube.

17. Performance, Efficiency and Color of Light. The Moore Tube

As seen, the values of terminal drop are very high, and as this voltage gives no equivalent of light, efficiency requires the use of such a long tube as to make the terminal drop a small part of the total voltage. In consequence hereof, the Moore tube is a very large unit of light and does not allow economical subdivision. It requires high-voltage alternating current, which is usually produced by a step-up transformer attached to the terminals of the tube. Intermittent direct current may equally well be used, but continuous direct current is not suitable, as the Geissler-tube conduction rapidly changes to arc conduction, and as the latter requires much lower voltage, leads to short-circuit.

In the Geissler tube the terminals disintegrate and the gas pressure falls fairly rapidly, possibly by absorption of the gas by disintegrated electrode material. As commercial illuminant, the Geissler tube therefore requires means of feeding gas intermittently into the tube. This is done in the Moore tube by an automatic valve.

As far as known, the most efficient Geissler-tube conductor is nitrogen. It gives a reddish-yellow light, of an efficiency which in very long tubes reaches values of 2.5 watts per candle-power, that is, about the same as the tantalum lamp, but of lower magnitude than the flame arc and the luminous arcs. Carbon dioxide CO_2 is also used as conductor. It gives a white light, but a lower efficiency. Mercury vapor gives it green light, but also at low efficiency.

The great advantage of the Moore tube is its low intrinsic brilliancy, and in the CO_2 tube its white color.

ARC CONDUCTION

18. Nature of the Arc Conductor. The Arc as Unidirectional Conductor. Rectification by the Arc. The Alternating-Current Arc. Constant-Pressure and Varying-Pressure Arcs.

In the electric arc the current is carried across the space between the electrodes or arc terminals by a stream of electrode vapor which

issues from a spot on the negative terminal, the so-called negative spot, as a high-velocity blast (probably of a velocity of several thousand feet per second). If the negative terminal is fluid the negative spot causes a depression, which is in a more or less rapid motion, depending on the fluidity. Before arc conduction can take place the vapor stream has to be produced, that is, an arc has to be started. This is done by bringing the electrodes into contact and then separating them, or by a high-voltage spark or a Geissler discharge, or by the vapor stream of another arc, or by heating the space between the electrodes, for instance, by an incandescent filament.*

The arc stream is conducting only in the direction of its motion, that is, any body which is reached by the arc stream is conductively connected with it, if electro-positive regards to it, but is not in conductive connection if negative or isolated. The arc thus is a unidirectional conductor, and as such has found an extensive use for the rectification of alternating current.†

Since the arc is a unidirectional conductor, it usually cannot exist with alternating current, since at the end of every half wave the vapor stream extinguishes, and at the beginning of the next half wave a new vapor stream in opposite direction has to be started. An alternating-current arc exists only if the conditions are such that at every half wave a new arc starts. This is the case if the voltage in the circuit is sufficiently high to send a disruptive spark across the gap at every half wave, or if the arc temperature is so high as to start the arc, as is the case with the carbon arc.‡

In their industrial application we may distinguish between constant-pressure arcs and varying-pressure arcs, that is, arcs in an enclosed space, usually a vacuum, in which the gas or vapor pressure varies with the current, etc. The only industrially used arc of the latter class is the mercury arc.

* See "Radiation, Light and Illumination," p. 106.

† On the arc as unidirectional conductor, see "Radiation, Light and Illumination," p. 111. On the electric characteristics of the mercury arc rectifier, see "Theory and Calculation of Transient Electrical Phenomena and Oscillations," by the author, p. 249.

‡ See "Radiation, Light and Illumination," p. 115.

CONSTANT-PRESSURE ARCS

19. Volt-Amperes and Volt-Length Characteristics of the Arc, $\frac{de}{di} < 0$

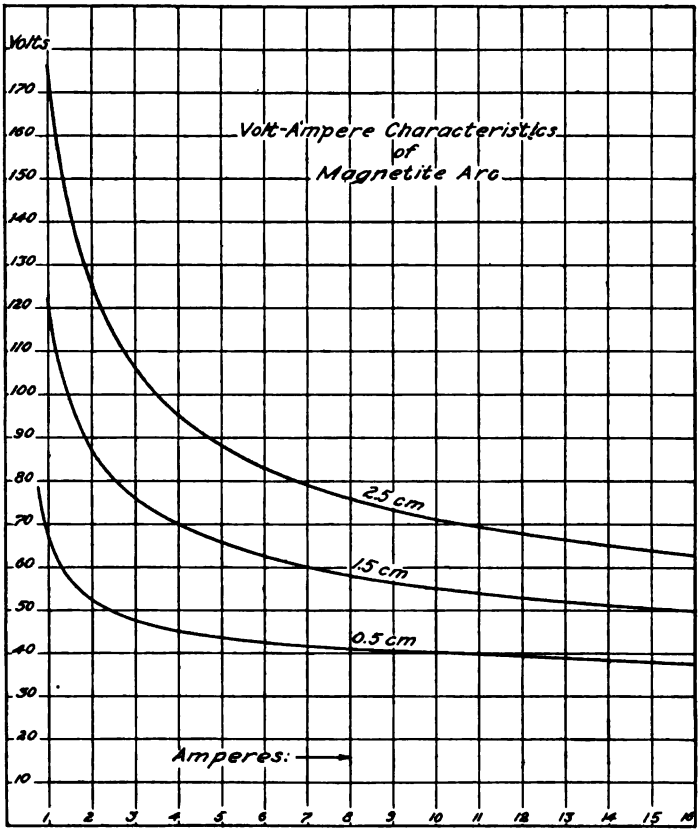

FIG. 6.

Characteristic of the arc as conductor is, that the voltage decreases with increase of current, that is $\frac{de}{di} < 0$ over the entire range. The volt-ampere characteristics of the arc therefore are curves of the shape shown in Fig. 6 for the magnetite arc, for the

arc lengths of 0.5, 1.5 and 2.5 cm. With increasing current the arc voltage decreases and approaches a finite limiting value, which with the magnetite arc is about 30 volts (about 36 volts with the carbon arc, 13 volts with the mercury arc, etc.). Inversely, with decreasing current the voltage increases, and tends towards infinity,

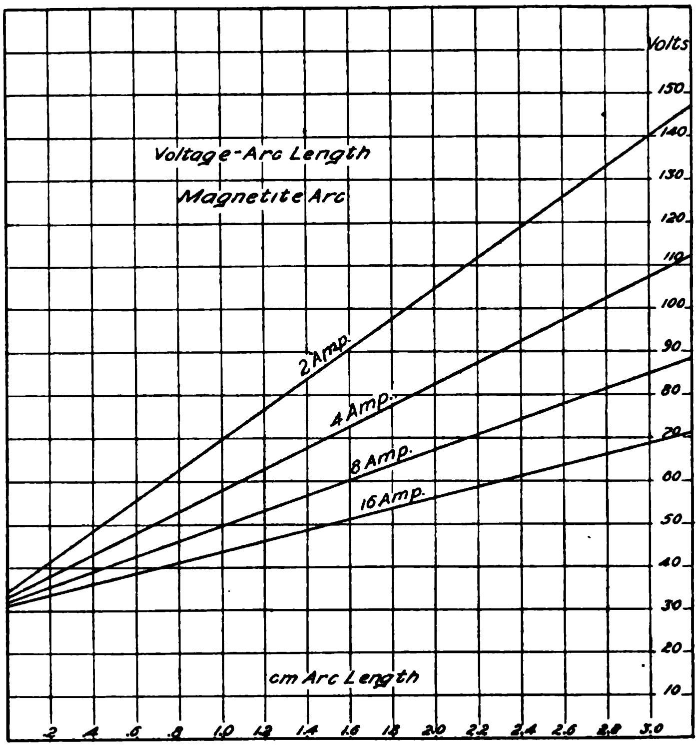

Fig. 7.

or rather probably the voltage required by the electrostatic spark, that is, by Geissler-tube conduction across the arc gap.

At constant current, with increasing arc length, the arc voltage increases very nearly proportional to the arc length, and the volt-length characteristics of the arc thus are practically straight lines, as shown in Fig. 7 for the magnetite arc of 2, 4, 8 and 16 amperes.*

* See "Radiation, Light and Illumination," p. 137.

20. Dependence of the Arc Voltage on Two Independent Variables, Current and Arc Length, Instability of the Arc on Constant-Voltage Supply. Necessity of Steadying Resistance or Reactance. The Stability Curve of the Arc

The arc as conductor in industrial illuminants thus differs from the solid conductors discussed in the preceding by two main characteristics:

a. In the solid conductors the relation between e and i is fixed, that is, e is determined by i, and inversely. In the arc, however, two independent variables exist, the current or voltage and the arc length. That is, e is a function of i as well as of l which can be expressed with fairly good approximation (except for very small currents, for which the voltage is higher than given by the equation) by the formula:

$$e = e_0 + \frac{c(l + \delta)}{\sqrt{i}},$$

where e_0, c and δ are constants, depending on the material of the electrodes, and more particularly on the negative electrode.

Least close is the agreement with above formula in the carbon arc, which in many other properties shows an exceptional character as result of the physical properties of carbon.*

b. In the arc it always is $\frac{de}{di} < 0$, while in the incandescent-lamp filaments it is $\frac{de}{di} > 0$.

Herefrom follows:

An arc is unstable and cannot be operated on constant-voltage supply, but with constant voltage at the arc terminals a slight momentary increase of the arc resistance, by requiring a higher voltage, decreases the current and thereby still further increases the required voltage and the arc goes out. Or, a slight momentary decrease of the arc resistance increases the current, thus lowers the arc voltage, thereby, at constant-supply voltage, increases the current and still further lowers the arc voltage, etc., and the arc short-circuits. The arc, however, is stable on constant-current supply.

The arc thus is essentially a constant-current phenomenon, its operation more steady on constant-current circuits, and additional apparatus is required for its operation on constant-potential cir-

* See "Radiation, Light and Illumination," p. 140.

cuits. That is, a resistance or reactance (with alternating arcs) must be inserted in series sufficiently large so that for the total voltage consumed by the arc with its steadying resistance $\frac{de}{di} > 0$. Thus, while in Fig. 8 the lower curve is the volt-ampere char-

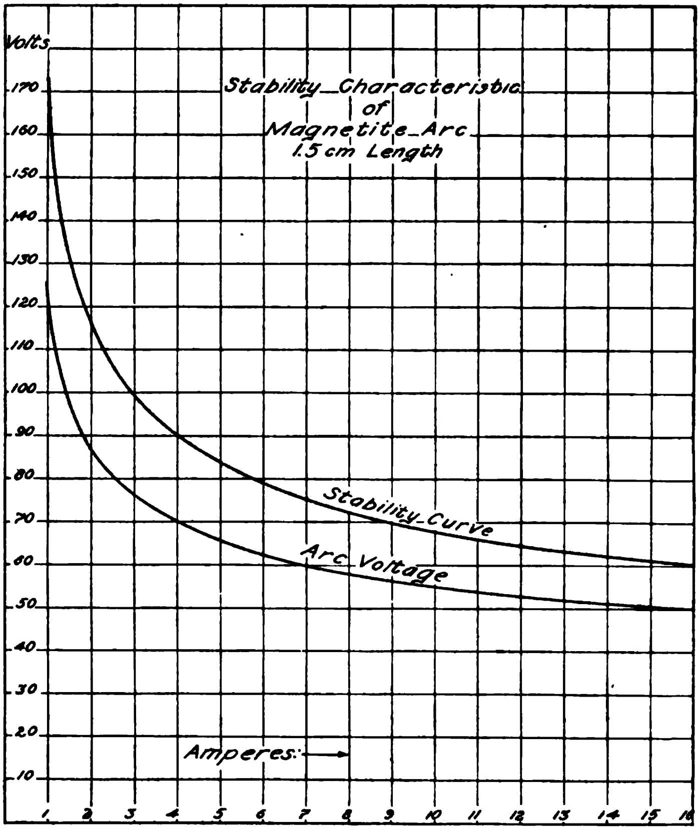

FIG. 8.

acteristic of a 1.5 cm. magnetite arc, to operate such an arc on a constant-potential supply a much higher voltage is required: the supply voltage must be greater than that given by the upper curve in Fig. 8 to give stable operation, and the more so the greater the required stability. This curve thus is called the "stability curve" of the arc.*

* See "Radiation, Light and Illumination," p. 142.

21. Instability of Parallel Operation of Arcs Without Steadying Resistances. Instability Due to Non-Inductive Resistance Shunt. Extinction by Shunted Capacity. The Arc as Interrupter. The Singing Arc

From the characteristic of the arc $\frac{de}{di} < 0$ also follows:

Several arcs cannot be operated in parallel except by giving each of them a steadying resistance or reactance as large as would be required for its operation on constant-potential circuit. Without this all the arcs go out but one.

Shunting the arc by a non-inductive resistance decreases its stability, and with decreasing resistance a definite value is reached at which the arc becomes unstable, that is, goes out. The stability of an arc thus can be measured by the current which can be shunted around it by a non-inductive resistance.

A condenser in shunt to the arc makes it unstable and interrupts it; a momentary increase of arc resistance, and thereby increase of arc voltage, increases the current shunted momentarily by the condenser, thereby decreases the arc current, and still further increases the arc voltage and shunts still more current into the condenser, etc. Even a small condenser in shunt to the arc thus puts it out. If the supply voltage is sufficiently high to restart the arc, after it is put out by a shunted condenser, the arc with shunted condenser then acts as an interrupter, causing rapid successive interruptions of the circuit with fairly constant frequency. The lower the stability of the arc the more sudden are the interruptions, and low-temperature arcs, as the mercury arc, thus give interruptions of extreme suddenness. Inversely, if the capacity is very small and the gas filling the space around the arc stream of low dielectric strength, as hydrogen or light hydrocarbons, the arc may start again, through the residual arc vapor, before completely extinguished, and the arc current becomes pulsating, the so-called "singing arc."

22. Stream Voltage and Terminal Drop of the Arc. Heating of the Terminals by the Terminal Drop. The Carbon Arc as Incandescent Radiator. Relation between the Efficiency of the Carbon Arc and the Size and the Life of the Terminals

Voltage, and therefore power, is consumed in the arc stream and at the arc terminals. The power consumed in the arc stream is

converted, more or less directly, into radiation, and if a large part of this radiation is in the visible range, as is the case with titanium, calcium and mercury vapor as conductors, the arc stream may be used as illuminant. If very little of the radiation is in the visible range—as is the case with carbon vapor as conductor—the arc stream does not contribute appreciably to the light given by the lamp.

The power consumed at the electrodes is partly converted into the latent heat of evaporation and the kinetic energy of the moving vapor stream (which is the arc conductor) largely into heat, especially at the positive terminal. If the arc terminals then are sufficiently small to reduce the heat conduction away from them, and of sufficiently refractory material to reach very high temperature, they may be used as radiators in giving light. The radiation then is due to incandescence or temperature radiation.

The latter is the case with the plain carbon arc lamp. When using pure carbon as arc-lamp electrodes the arc stream gives very little light, and that of a useless, violet color. Considerable heat is, however, produced at the positive electrode, and if this is not too large its tip reaches a very high temperature: the boiling point of carbon, and then gives light by temperature radiation, practically black-body radiation. The plain carbon arc therefore gives light by incandescence, just like the carbon-filament incandescent lamp, and the arc stream in the former is merely the heater which raises the temperature of the radiator, the positive-electrode tip, to a high temperature, and the much higher radiation efficiency and white color of the carbon arc, compared with the carbon filament, is due to the higher temperature of the former. Nevertheless, while the radiation efficiency of the carbon arc is the highest which can be reached by black-body radiation, it is very much lower than the efficiencies available by luminescence of the arc stream.

Of the heat produced at the positive terminal of the carbon arc only a part becomes useful as incandescent radiation; the rest is conducted away through the electrode, carried away by air currents, etc. The lower this loss, that is, the smaller the electrodes, the higher is therefore the efficiency, and with very large electrodes the heat conduction becomes so large that the electrode tips do not reach any more the temperature of efficient radiation, and the efficiency vanishes. The efficiency of the carbon arc lamp thus depends on the size of the electrodes, and increases with decreasing

size. However, with decreasing size, the consumption of the electrodes by combustion increases, and thus requires more frequent trimming of the lamp, that is, higher cost of maintenance.

23. *The Open Carbon Arc or Short-Burning Arc Lamp. The Enclosed Carbon Arc or Long-Burning Lamp. Its Inferiority in Efficiency*

The first carbon arc lamps were operated with high current: on 9.6 amperes constant direct-current circuits, with electrodes, which were fairly small relative to the current, and therefore gave fairly good efficiencies: about 1 watt per candle-power. However, under these conditions, the rate of consumption of the electrodes was very rapid, and electrodes of the greatest length, which could conveniently be used in a lamp, lasted only a few hours. As result thereof, twin carbon lamps were designed, and were in extensive use. The high cost of operation, due to the required daily trimming, of these so-called "open arc lamps" or "short-burning arc lamps" led to the development of the enclosed carbon arc lamp. In this type of lamp the arc is enclosed in a small, nearly air-tight glass globe, and the rate of consumption of the electrodes thereby greatly reduced and a longer life of electrodes secured. As the retarded combustion of the electrodes resulted in their assuming a more flattened shape, the arc length had to be increased to limit the obstruction of the light issuing from the positive electrode by the shadow of the negative electrode. The higher arc voltage resulting herefrom required a decrease of current to retain the same power consumption, and while the open arc operated at 40 to 45 volts on 9.6 amperes circuits, the enclosed arc lamp consumes 70 to 75 volts on 6.6 or 7.5 amperes circuits. As the same size of electrodes was retained, or the size even increased, to get a long life, while the current and thereby the luminous area of the electrodes was reduced, the heat losses by conduction and convection were greater in the enclosed arc, and the efficiency therefore lower than in the open arc. Nevertheless, the advantage of lower maintenance cost resulting from the less frequent trimming, weekly with the enclosed arc lamp against daily with the open arc lamp, has led to the entire abandonment of the latter, and while open arcs have survived in a few cities they have practically ceased as an article of manufacture.

24. Uneconomical Operation of Continuous-Current Series Arc Circuits. The Series Alternating Enclosed Arc Lamp. Its Very Low Efficiency

In regard to the electrical-power supply, the enclosed arc lamp is inferior to the open arc lamp, since with the former the higher voltage and lower current gives, with the same maximum voltage of the constant-current circuit, a smaller unit, and with direct current an arc machine was required for each circuit. This was such an economical disadvantage that the direct-current series enclosed carbon arc lamp is used to a limited extent only in such places where efficiency of light production is essential, and the illuminant, which is most universally used for street lighting, is the constant-current alternating enclosed carbon arc lamp. With this lamp, operating from constant-current transformers, the small size of the individual arc circuit is not such a serious handicap.

The economic disadvantage of numerous small machine units, which handicapped the series direct-current arc lamp, has been eliminated by the development of the constant-current mercury arc rectifier system, which permits operation of constant-direct current arc circuits from constant-current transformers. This development, however, was too late to help the direct-current carbon arc, but, coming after the development of the luminous arc, it led to the rapid introduction of the latter in place of the carbon arc.

The efficiency of the alternating-current carbon arc lamp, however, is much lower than that of the direct-current lamp: in the alternating-current lamp the losses of heat through the electrodes are more than doubled: while the heat loss by conduction and convection is continuous, heat is produced at either electrode mainly during that half wave of current where the electrode is positive, and then only during that part of this half wave where the current is high. Thus, while the alternating-current carbon arc lamp gives light from both electrodes, its efficiency of light production is much lower, and with the standard series enclosed alternating-current arc lamp at 70 to 75 volts per lamp, on 6.6 and 7.5 amperes constant alternating-current circuits, the specific consumption is up to 2.5 to 3 watts per candle-power, and even higher, that is, the efficiency has dropped down below that reached with modern incandescent lamps.

In spite of its very low efficiency, the small amount of attention required by it, and the convenience of operation from alternating-

current supply circuits, through constant-current transformers in street lighting, has led to the almost universal adoption of the alternating-current enclosed carbon arc lamp, and probably more lamps of this type are used in street lighting than of all other types together.

25. Replacement of the Enclosed Alternating Carbon Arc by the Magnetite Arc Lamp in Street Lighting, by the Intensified Arc or the Tungsten Incandescent Lamp in Indoor Lighting. The Intensified Arc Lamp

However, with the development of high-efficiency incandescent lamps, the position of the standard enclosed alternating carbon arc lamp became untenable, and while it is still being used in enormous numbers it is being rapidly replaced by the magnetite arc lamp in street lighting, and by the intensified arc lamp and the tungsten incandescent lamp in indoor lighting, and the manufacture of the enclosed alternating carbon arc lamp has greatly decreased.

While thus the enclosed carbon arc lamp is rapidly disappearing from the streets, before the luminous arc, for indoor lighting, where the luminous arc and the flame arc are handicapped by being too large units of light, and by producing smoke and gases, and the tungsten lamp is the only competitor, the enclosed carbon arc lamp is retaining its field as the "intensified arc lamp." Since the efficiency of the carbon arc lamp increases with decreasing size of carbons, by the use of very small carbons in an enclosed type of lamp, a very good efficiency, about 1 candle-power per watt, is reached in the so-called "intensified arc lamp" on direct current as well as on alternating current. The life of the electrodes of the intensified arc lamp is shorter than that of the enclosed arc lamp of old, but as this lamp is mainly used indoors, where usually the daily operation is only a few hours, the life is sufficient to reduce the frequency of trimming satisfactorily, and the higher efficiency and white color of light gives to the intensified arc an advantage over the tungsten lamp in those cases where large units of light are permissible.

26. The Luminous Arc and the Flame Arc. Their Characteristic Differences, Advantages and Disadvantages. The Magnetite Arc

The carbon arc is an illuminant using a solid radiator and producing light by incandescent radiation, like the incandescent lamps.

In all other arcs luminescence plays an essential part, and all or most of the light is given by the arc flame as vapor conductor.

These luminescent arcs can be divided into two classes: the *luminous arcs* and the *flame arcs*.* In the luminous arcs the luminescent material is introduced into the arc stream by electro-conduction from the negative, that is, is used as arc conductor. Typical arcs of this class are the so-called magnetite arc and the mercury arc. The latter, as vacuum arc, will be discussed later. In the flame arcs the luminescent material is introduced into the arc stream by heat evaporation, either from the positive as the hotter terminal, or from both terminals. The characteristic difference resulting herefrom is, that in the luminous arc the temperature of the electrode has no direct relation to the efficiency, and the electrodes thus can be maintained at such low temperature as to consume very slowly. The luminous arc thus lends itself to the production of long-burning arc lamps, that is, lamps requiring very infrequent trimming, and the size of the electrodes is usually made such as to give a life of 100 to 200 hours as the longest time which it is advisable to allow a lamp to burn without cleaning the globe, and other attention. The positive electrode of the luminous arc is entirely immaterial, and usually made of some metal of high heat conductivity so as not to consume appreciably, that is, of a life of some thousand hours.

At the same time the number of materials which can be used in the luminous arc is much more limited, the difficulties of design so as to get steady operation, greater than with the flame arc, and no successful luminous arc has yet been commercially developed for alternating-current circuits, but the luminous arc has been developed for direct-current circuits in the so-called "magnetite arc lamp," also occasionally called "metallic-oxide arc lamp" and "ferro-titanium arc lamp." In this the negative electrode is a mixture of the oxides of iron, titanium and chromium (magnetite, illmenite, rutile, chromite), usually enclosed by a thin iron shell. The positive electrode is a permanent part of the lamp.

The magnetite arc lamps are operated on constant direct-current circuits of 4 amperes and of 6.6 amperes, with about 75 volts per lamp, usually from constant-current transformers through mercury arc rectifiers.

* See "Radiation, Light and Illumination," p. 123.

27. *The Flame Carbon Arc. Relation between Size of Electrode and Efficiency. The Short-Burning and the Long-Burning Flame Carbon Arc. The Yellow Color of the Flame Carbon Arc. Titanium, Calcium and Mercury as the Three Most Efficient Arc-Stream Radiators*

In the flame arcs the luminescent material is introduced into the arc stream largely by heat evaporation, a high temperature of the positive electrode thus is essential, and, to some extent, similar relations exist between the size and therefore temperature of the electrodes and the efficiency. Carbon is always used as the main electrode material, since carbon gives the hottest arc, and also the steadiest arc, and the inherent steadiness of the carbon arc has made the development of the flame carbon arc lamp less difficult and therefore more rapid than that of the luminous arc, and made it possible to operate such arcs on alternating-current circuits as well as on direct-current circuits.

Since, however, carbon rapidly consumes, and the size of the electrodes cannot be materially increased without loss of efficiency, the flame carbon arc lamp is essentially a short-burning arc lamp, requiring daily trimming. This has in this country excluded its use for general street illumination, and restricted it largely to decorative lighting.

To make the flame carbon arc long burning requires enclosing it similar as with the enclosed plain carbon arc to reduce the access of air. Since, however, by the consumption of the electrodes the luminescent materials contained therein escape as a smoke, means are required to deposit this smoke, by a circulating system, at some place where it does not obstruct the light by deposition on the globe. A number of such long-burning flame lamps have been designed, but none of them has yet found an extended industrial introduction, probably largely due to conditions outside of the lamp mechanism: the yellow color of the light, the large unit of light, the expense of the electrodes, lack of steadiness, etc.

The only materials which thus far are used in flame carbon arcs as luminescent matter are calcium compounds, as fluorides, borates, phosphates, tungstates, etc. They give a very high efficiency, but a yellow light. White-flame carbons have not yet been introduced of an efficiency comparable with that of the more efficient yellow-flame carbons.

To some extent the flame carbon arc stands intermediate between the luminous arc and the plain carbon arc: the plain carbon arc gives light only by incandescence of the electrode terminals, the luminous arc only by luminescence of the arc stream, and the flame carbon arc gives most of its light by luminescence of the arc stream, but also some light by incandescence of the positive carbon terminal.

It is interesting to note, that thus far only three materials have been found which in the arc give very high efficiencies of light production, reaching in large units values of 3 to 4 candles per watt; titanium, calcium and mercury. The first gives a white light, and is used in the magnetite arc; the second gives a yellow light, and is used in the flame carbon arc; and the third is restricted to the vacuum arc.

28. *The Mechanism of the Arc Lamp: Starting Device, Feeding Device, Steadying Device, Shunt Protective Device, Damping Device. Series Lamp, Shunt Lamp, Differential Lamp*

Due to the nature of the arc, as discussed above, all arc lamps require an operating mechanism.

Since the arc does not start spontaneously, a starting device is required. This consists of a mechanism which brings the electrodes together, thereby closes the circuit between them, and then separates them and so starts an arc.

Since, in supplying the vapor conductor of the arc stream, the electrodes consume, more or less rapidly, a feeding device is necessary, that is, a mechanism which gradually moves the electrodes together so as to maintain the proper length of the arc stream.

In constant-potential or multiple lamps a steadying device is necessary since, as seen, the arc is unstable on constant potential. This consists of a resistance in direct current, of a reactance in alternating-current arc lamps, which is connected in series to the arc, and usually made adjustable so as to accommodate the lamp to the different supply voltages met in electric-supply systems.

In constant-current or series lamps a shunt protective device is necessary to close the circuit around the arc in case the circuit in the lamp opens by breakage or consumption of the electrodes. This usually consists of a shunt resistance, connected across the lamp terminals by a potential magnet.

In addition thereto dashpots or other retarding devices are necessary to slow down the motion of the operating mechanism so as to draw the arc sufficiently slowly not to break, and to guard against over-reaching of the feeding mechanism.

The operating mechanism is actuated by electromagnets or solenoids, frequently in combination with weights, and rarely springs, as the latter have usually proved unreliable in continuous operation.

If only series magnets are used the lamp is called a series lamp; if only shunt magnets are used it is called a shunt lamp; if series and shunt magnets are used, a differential lamp. The series lamp regulates for constant current in the lamp, thus is not applicable where several lamps are connected in series; the shunt magnet regulates for constant voltage, irrespective of the current, and the differential lamp regulates for constant relation of current and voltage. The latter type is most commonly used.

The different forms of arc-lamp mechanisms which are in industrial use cannot be described here, but may be studied from the publications of the various arc-lamp manufacturers, which give detailed information, or by inspection of the exhibit of typical arc lamps shown here,* and only some general principles can be discussed, which may enable a judgment of the correctness of individual operating mechanisms.

29. The Effective Resistance of the Arc. Relation between Arc Length and Efficiency. The Short-Carbon Arc and the Long Luminous and Flame Arcs

The effective resistance of the arc is not constant, but continuously and often rapidly varies or pulsates somewhat. The arc conductor is a vapor stream of a temperature very much higher than the surrounding air, and thus, even when well screened, more or less affected by air currents, drafts, etc. In the plain carbon arc lamp, in which the heated terminals are the radiator, and the voltage consumed by the arc stream is wasted, the arc length is made as short as possible, without obstructing the light by the shadow of the electrodes, and the fluctuations of the arc resistance therefore are moderate. In the flame arcs and luminous arcs, however, in which the light is given by the arc stream, and the

* Also see "Radiation, Light and Illumination," p. 151.

potential drop at the terminals represents largely wasted power, efficiency requires a long arc stream, and this is more sensitive to air currents, thus the fluctuations of the arc resistance are greater, especially when very small currents are used, as necessary in smaller units of light.

The problem in arc-lamp design thus is to devise an operating mechanism which regulates as closely as possible for constant production of light by the arc lamp, and at the same time permits the use and economical operation of the arc lamp on existing distribution systems.

80. *Regulation of the Arc Lamp for Constant Light Flux: the Floating System of Control of the Carbon Arc and its Advantages. Fixed Arc Length Required by the Luminous Arc. Its Difficulties in Constant-Potential Lamps. The Compromise Control of the Flame Carbon Lamp*

In the plain carbon arc the light production depends on the current, but not on the arc length, provided the latter is sufficient to minimize the shadow of the electrodes. Regulation for constant light flux, therefore, is closest by control for constancy of current. Thus the series magnet, which varies the arc length to maintain constant current, is most satisfactory in constant-potential lamps, while in constant-current lamps the controlling mechanism merely has to maintain the arc length sufficient for reducing the electrode shadows, and not too long to give too much waste of power. As the arc length has no direct effect on the light, a floating system of control thus can be used, and is always used, as being easiest to operate. That is, one or both carbons are held floating by the counteracting forces of shunt and series magnet, or of series magnet and weight, and continuously move in adjusting the arc length to the fluctuations of arc resistance. The voltage at the terminals of such a constant-current arc lamp thus shows very small fluctuations.

Entirely different, however, are the conditions in the luminous arc. In this the light flux is proportional to the current and the arc length, and any fluctuation of the arc length, by a floating system of control, would give a corresponding fluctuation of light flux, and is therefore objectionable. A fluctuation of arc resistance is accompanied by a change of luminosity, such that an increase of arc resistance and therefore of arc voltage at constant arc length usually gives a decrease of luminosity, and thereby of light flux;

and regulation for constant light flux therefore would require an increase of arc length at an increase of arc voltage caused by an increased arc resistance. The floating system of control, by shortening the arc at an increase of arc voltage, thus in this case controls in the wrong direction and accentuates fluctuations of light, and the nearest approach to proper regulation of light flux is given by maintaining constant arc length. In luminous arc lamps therefore always, as far as it is possible, a control for fixed arc length is used. That is, the arc terminals are locked in position at a fixed distance, and at intervals, depending on the rate of consumption, this distance is adjusted by resetting the arc. This fixed arc-length control gives a curve of terminal voltage, which fluctuates considerably, following the fluctuations of the arc resistance. In constant-current circuits this is not objectionable, as the voltage fluctuations of the numerous lamps in series with each other superpose to a constant total voltage. In multiple or constant-potential lamps, however, the fluctuations of arc voltage may interfere with the operation, and thus either a very large inductance has to be used in series to the arc, to steady the current, or regulation for constant light flux more or less sacrificed by the use of a floating system of control, and as the result, the multiple-luminous arc lamp is less steady than the series arc lamp.

In flame arc lamps, usually larger currents and thus longer arcs are employed, and a sluggish floating mechanism, if limited to work over a moderate range only, is less objectionable, but nevertheless the light flux of the lamp is less steady than in the plain carbon lamp, and one of the main objections of the flame arc is its inferiority in steadiness of the light flux.

31. *Classification of Arc Lamps. The Most Important Forms of Arc Lamps*

In classifying the different types of arc lamps we have:

By the nature of the light production: the plain carbon arc, the flame carbon arc and the luminous arc, the latter including the mercury arc as vacuum arc.

By the life of the electrodes: the short-burning arc and the long-burning arc. The former giving a life of electrodes of from 8 to 20 hours, depending on the current and the size of electrodes, the latter a life of 50 to 250 hours, or even much more, as with the mercury arc.

By the protection of the arc against the access of air: the open arc and the enclosed arc.

By the nature of the supply circuits: the constant-potential or multiple arc lamp and the constant-current or series arc lamp.

By the arrangement of the electrodes: the vertical arc and the horizontal arc. In the former the electrodes are arranged vertically above each other, and the maximum light flux thus issues in the horizontal direction, except in the direct-current plain carbon arc, in which the maximum light flux is downwards from the upper positive electrode as radiator. In the horizontal arc the electrodes are converging downwards, and the maximum light flux thus is in the downward direction.

The most important forms of arc lamps thus are:

The *open* plain *carbon arc.* A short-burning arc, which has survived in a few cities on 9.6 amperes series circuits.

The *enclosed* plain *carbon arc.* Long burning, for *multiple* and for *series* circuits, on *alternating* and on *direct* current. The majority of the arc lamps now in use are series alternating enclosed carbon arcs, on 6.6 amperes and on 7.5 amperes series circuits. This type of arc is, however, rapidly disappearing, due to its low efficiency.

The *intensified arc.* It is an enclosed plain carbon arc, medium long burning, gaining its efficiency by the small size of the electrodes. It is mainly used for indoor lighting of high efficiency and white color, on constant-potential *direct-* and *alternating-*current circuit.

The *yellow-flame arc.* Usually an open and short-burning arc, with converging carbons for downward distribution of light, used mainly for outdoor decorative lighting, and to some extent for second-class interior lighting. Its disadvantage is the yellow color of the light.

The *magnetite arc,* mainly used on 4 amperes and 6.6 amperes direct-current series circuits, for street light, where it is taking the place of the series enclosed carbon arc. It is an open, long-burning arc.

The *mercury arc* or vacuum arc, mainly used for indoor lighting of high efficiency and steadiness. Its disadvantage is the green color of the light.

32. Increase of the Efficiency of the Arc with Increasing Size of the Light Unit. Relation between the Efficiency of the Arc Lamp and the Current, Arc Length and Power, at Constant Arc Length, Constant Current and Constant Power. The Conditions of Maximum Efficiency

Unlike the incandescent lamp, in which the efficiency of light production remains practically constant over a wide range of units of light, the efficiency of the arc lamp increases with increasing power consumption and thus increasing size of unit of light, but

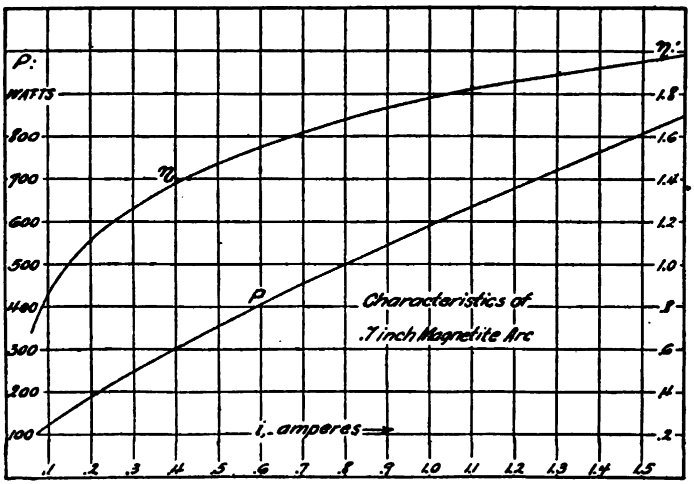

FIG. 9.

falls off with decreasing size of the light unit, and the arc lamp thus is essentially a large unit of light, but for small units does not have the efficiency to compete with the modern incandescent lamps, while inversely for large units it reaches efficiencies of higher magnitude than possible with incandescent lamps.

The relation of the efficiency of light production by the arc to the power consumption can, with fair approximation, be calculated, especially for the luminous arc.

For instance, in the series direct-current magnetite arc, the approximate equation of the arc voltage is

$$e = 30 + \frac{123(1+.05}{\sqrt{i}} \qquad (1)$$

where the arc length l is given in inches, and the approximate expression of the light flux Φ, in mean spherical candle-power, is:

$$\Phi = 150\,li \qquad (2)$$

(assuming, as approximately the case, the light flux as proportional to the arc length and the current).

For constant arc length l then follows, from equations (1) and (2), for different values of current i, the power consumption $p = ei$ and the efficiency η. Curves, for the arc length $l = .7$ inches, are given in Fig. 9.

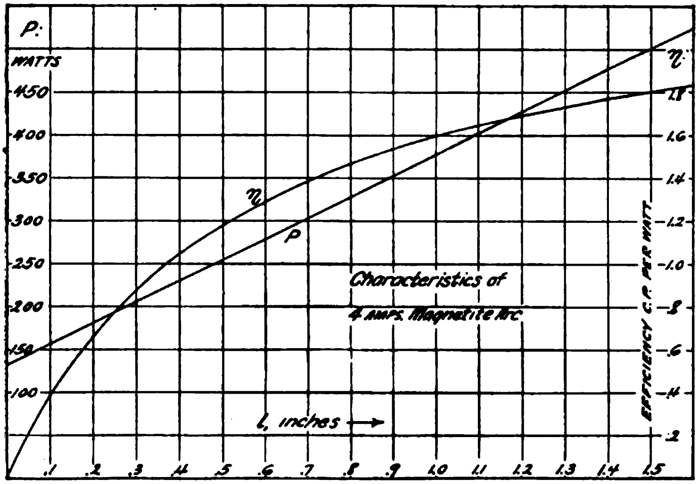

FIG. 10.

For constant current, $i = 4$ amperes, curves of the power consumption and of the efficiency for different arc lengths are given in Fig. 10.

As seen, with increasing current at constant arc length, and with increasing arc length at constant current, the efficiency increases, but the power consumption also increases.

For constant power consumption, $p = ei$, then follow, from equations (1) and (2), values of arc length, arc voltage and efficiency. They are plotted, for 300 watts and 500 watts power consumption in the arc, in Fig. 11 as function of the current. As seen, with

increasing current at constant power consumption, the efficiency increases to a maximum—which is higher with the 500-watt arc than with the 300-watt arc—and then decreases again.

Determining then the condition of maximum efficiency, as func-

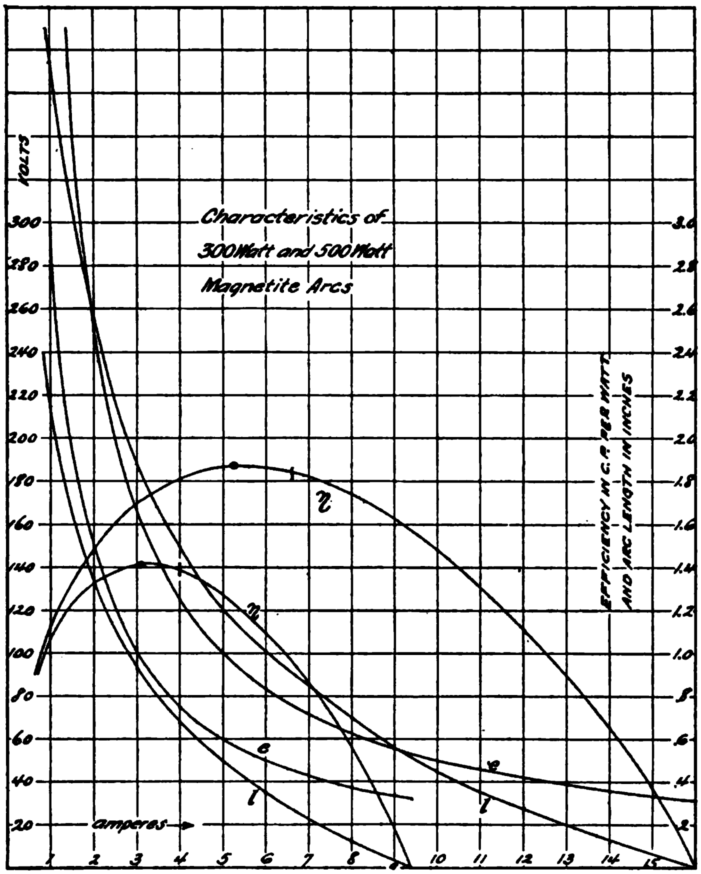

FIG. 11.

tion of power consumption in the arc, gives the curves shown in Fig. 12. As seen, to operate at maximum efficiency, with increasing power consumption the current in the arc and the arc length has to be increased, while the arc voltage remains nearly constant. The efficiency rises rapidly with increasing power consumption.

33. Comparison of the Arc Lamp and the Incandescent Lamp

As seen from Fig. 12, the efficiency of the tungsten incandescent lamp, of approximately 0.66 candle-power per watt, is reached at 70 watts power consumption.

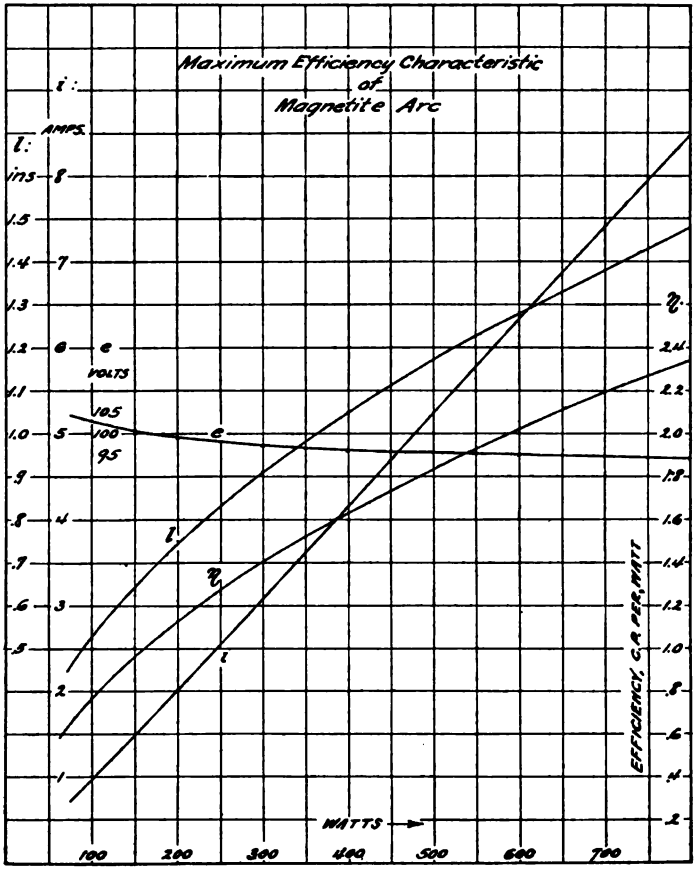

FIG. 12.

Considering, however, that the efficiency is not the only factor in the cost, but that the cost of attention, trimming, etc., also enters, furthermore, that at the lower consumption some efficiency would have to be sacrificed to steadiness by increasing the current beyond, and therefore reducing the arc length below that corresponding to maximum efficiency, the dividing line between tungsten

incandescent lamp and magnetite arc lamp for use in street lighting probably lies at about 100 to 150 watts power consumption, depending on the individual conditions; below this the tungsten lamp above the magnetite arc is more efficient, other things being equal.

Similar relations exist with other types of arcs: with the flame carbon arcs, approximately the same relations would exist—except that the numerical values of efficiency are proportionally changed—provided that the size of the flame carbons is changed proportional to the current. If the same size of flame carbons is retained, the efficiency falls off more rapidly with the decrease of current, and increases more rapidly with its increase, due to the change of the rate of evaporation. However, in economical comparison with the tungsten lamp, the very much higher cost of trimming, with the short-burning flame lamp, would probably shift the dividing line of economical use, between the tungsten lamp and the arc lamp, to higher values of power, while more efficient long-burning luminous arcs would shift it to lower values of power.

VACUUM ARCS

34. The Low-Pressure Mercury Arc in the Glass Tube. The High-Pressure Mercury Arc in the Quartz Tube. Their Characteristics

The only industrially used vacuum arcs are the mercury arcs: the low-pressure mercury arc, operated in a glass tube, and the high-pressure mercury arc, operated in a quartz tube.

In the mercury arc the terminal drop is constant, and about 13 volts, while the stream voltage is proportional to the arc length and independent—within a certain range—of the current, but depends upon the diameter of the arc tube, and on the vapor pressure; it increases with decreasing tube diameter and with increasing vapor pressure, so that in an arc tube of about 2 cm. diameter and a high vacuum it is as low as 0.5 volts per centimeter, and rises to 8 to 10 volts per centimeter in a tube of 1 cm. diameter at a mercury-vapor pressure about equal to atmospheric pressure.

The mercury arc is a luminous arc and stands at the one end of a series, of which the carbon arc stands at the other end; while the latter is the hottest arc the former is the coldest, and in the low-pressure mercury arc in a glass tube the temperature of the arc stream is only about 200° to 250° C.

Like all arcs, it requires a starting mechanism; the feeding is done by condensing the mercury vapor in a condensing chamber, and returning it to the negative electrode by gravity.

A valuable characteristic of the mercury arc is, that it can be built of very good efficiency in smaller units than any other arc: as low as 80 to 100 watts.

In the high vacuum of the mercury arc in the glass tube the arc length is very great at moderate voltages, and mercury arc tubes of over 3 feet length are operated on 110-volt circuits; in the quartz-tube arc, due to the high vapor pressure, the arc length is short and comparable with that of other arcs of the same voltage; an arc length of 8 inches requires a 220-volt supply.

Like all arcs, the mercury arc requires a steadying resistance on constant-potential supply circuits.

The light of the mercury arc has the advantage of great steadiness and high efficiency, but the disadvantage of a green color, which is almost entirely deficient in red rays, and therefore greatly distorts colors.

SENSITIVITY TO VARIATIONS OF THE ELECTRIC-POWER SUPPLY

35. *Comparison of the Various Forms of Incandescent Lamps and Arc Lamps Regarding Their Sensitivity to Variation of the Electric-Power Supply:*

The various forms of electric illuminants must find their place in existing electric distribution systems, either constant-potential or constant current. No electric circuit, however, maintains absolutely constant-potential respectively constant current, but fluctuations of greater or lesser extent occur, and it thus is of importance to know the sensitivity of the illuminants to variations of the supply circuit. Since the limit of sensitivity of the human eye for changes of light flux is not much below 2 per cent, a sudden change of light flux of 5 per cent is not seriously objectionable, and a gradual change even of 20 per cent is hardly appreciable. The permissible range of sudden and of gradual variation of the electric-supply system, and inversely, in a system of given regulation, the degree of satisfactoriness of an illuminant would then be determined by the ratio of the change of light flux to the change of the electric supply causing it.

In the following are given a number of approximate values of the

percentage change of light flux of various electric illuminants, resulting from a change of the electric-supply voltage, current or power by 1 per cent.

In the calculation of the incandescent lamp values, the curves of Fig. 2 have been used; the arc-lamp values are calculated from the characteristic curves of the arc, equations (1) and (2). They depend to a greater or less extent on arc length, per cent of steadying resistance, etc., and thus can be approximate only.

APPROXIMATE VARIATION OF CANDLE-POWER, IN PER CENT

For 1 per cent variation of—	Power	Voltage	Current
Incandescent lamps:			
Treated carbon filament	2.8	5.6	5.6
Gem filament	2.5	4.45	5.7
Tungsten filament	2.33	3.75	6.25
Constant current arcs—75 volts per lamp:			
Magnetite arc lamp	1.42	...	1.0
Flame carbon arc, differential control	1.7	3.4	3.4
Flame carbon arc, shunt control	1.55	...	1.55
Constant potential arcs—110-volt supply, 33 per cent steadying resistance:			
Mercury arc	.75	3.0	1.0
Magnetite arc (constant arc length)	.88	7.5	1.0
Flame carbon arc, differential control	1.7	3.4	3.4
Flame carbon arc, shunt control	1.17	4.7	1.55
Flame carbon arc, series control	2.65	2.65	...

Incandescent lamps in general are much more sensitive to changes of supply than arc lamps, that is, require a closer regulation of the electric supply.

Especially the arcs with constant fixed arc length, as the magnetite arc and the mercury arc, are very little sensitive to changes of current, while the arc lamp with floating-feed and differential control is most sensitive to current changes, though less so than the incandescent lamp.

Inversely, on constant-potential supply, the constant-pressure arc with fixed arc length shows the greatest sensitivity to voltage variations. This depends on the amount of steadying resistance, and decreases with increasing steadying resistance, while with less than 33 per cent steadying resistance the sensitivity increases so that the arc soon becomes inoperative. The least sensitivity on multiple circuit is afforded by series control.

It thus would follow, that the incandescent lamps with high-positive temperature coefficient have an advantage on constant-potential supply, but a corresponding disadvantage on constant-current supply. On constant-current circuits the arc lamps with fixed arc length, as the magnetite and mercury, would be most constant in their light production, and next thereto the lamps with shunt control, while inversely on constant-potential circuits these two operating mechanisms are most sensitive to voltage variations.

V (1)

GAS AND OIL ILLUMINANTS

By Alex. C. Humphreys

CONTENTS

Introduction.
- Scope of lecture.
- Brief reference to the special character of the illuminants considered.
- Petroleum and by-products—kerosene.

Illuminants considered.
- Pintsch gas.
  - Brief history.
  - Present extent of use.
  - How made.
    - Externally heated retorts—low pressure.
    - Internally heated generators, low pressure and high pressure.
  - Special characteristics.
  - How employed.
    - Lighting of railroad cars.
    - Lighting of buoys, beacons, lightships, etc.
  - Special appliances—especially pressure regulators, car lamps and buoy lanterns.
  - Pintsch system provides for scientific distribution of light.
- Carburetted-air gas.
  - Brief history.
  - Present extent of use.
  - Produced from certain hydrocarbons.
  - Special characteristics.
  - How employed.
    - Isolated plants.
    - Town plants.
  - Special appliances.
- Acetylene.
  - Brief history.
  - Present extent of use.
  - Carbide of calcium—CaC_2.
  - How produced from CaC_2.
  - Special characteristics.
  - Liquefaction.
  - Special precautions.

How employed.
- **Isolated plants.**
- **Town plants.**
- **Portable lamps and lanterns.**

Special appliances.

Introduction

Those who unselfishly have taken the initiative in arranging for this course of lectures on the science and art of illuminating engineering, sparing neither time, thought nor effort, should be exempt from all unfriendly criticism. Then it should be understood that in 36 lectures, treating of 19 divisions of the subject, not more can be done, certainly with regard to some of the divisions and subdivisions, than point the way to those who desire to devote themselves seriously to the study and practice of illuminating engineering.

This lecture is one of two which are expected to cover "Gas and Oil Illuminants." To Professor Whitaker has been assigned the open flame and the incandescent mantle, and to me Pintsch gas, carburetted-air gas and acetylene. It must be apparent that the hour and a half allotted to each lecture is entirely inadequate for a comprehensive consideration of the three systems named.

It should be understood that this lecture, notwithstanding the sub-title of Part V, is not intended to cover coal gas, water gas or natural gas, which are the gas illuminants most generally distributed and which, especially if taken together, furnish more artificial illumination than electric light together with the three illuminants here to be considered.

As we proceed it will be seen that Pintsch gas, carburetted-air gas and acetylene do not compete with coal gas, water gas or natural gas, but are employed where these are not commercially available or obtainable, or *where a special character of service is required.*

Of these three sources of artificial illumination, two, namely, Pintsch gas and air gas, are made from oil. Pintsch gas is produced by the destructive distillation of petroleum oil. It is not to be understood that the manufacture of oil gas is confined to this process. Oil gas has been employed to a considerable extent in the United States and Europe for the illumination of small towns, factories, etc. Oil gas was so employed before it was applied in

compressed form to car lighting, and patents for oil-gas manufacture were granted in the early part of the last century.

In some few cases compressed oil gas has been employed for the lighting of small towns, the compressed gas being delivered in cylinders instead of through mains laid in the thoroughfares; these undertakings were short-lived. In Scotland, prior to the production of petroleum in large quantities, a high candle-power gas was made from oil distilled from rich shales.

By far the most extensive use of oil in the making of illuminating gas has been in the manufacture of carburetted water gas.

Although the title of Division V includes oil as an illuminant, neither Professor Whitaker nor I are expected to consider it as a direct source of illumination. When we realize that refined kerosene oil is used throughout the whole civilized world, competing with all other sources of artificial illumination covered in these lectures and relied upon where these are not to be found, this well serves to illustrate the fact that the 36 lectures cannot be made to cover, even superficially, the whole field of artificial illumination.

In this connection, let me refer you to "Petroleum and Its Products," by Sir Boverton Redwood, 2d Edition, 1906, two volumes, published by Charles Griffen & Company, London. This work is most valuable in itself, and also for the extensive bibliography annexed.

Redwood gives an interesting and instructive history of the petroleum industry, beginning with a reference to an account written by Herodotus, 450 B. C., of a well producing "asphalt, salt and oil." Petroleum is now being produced in all parts of the world, and in many places in large quantities. Vast quantities have been discovered recently in Mexico, this oil being unusually rich in asphalt.

The production of oil from coal and shale is of interest, especially as much of scientific and practical value was learned in the course of the evolution of the process and apparatus employed.

I presume that other of the lectures included in this course will give some account of the several by-products from the distillation of petroleum which have been and still are employed in manufacturing water gas and enriching coal gas, and of the commercial utilization of these and other by-products of kerosene

manufacture which has enabled the great oil companies, especially the Standard, to produce kerosene at a minimum cost.

The internal combustion engine, particularly as used in motor cars and motor boats, has, within the last few years, developed an extensive and rapidly growing market for the more volatile of the distillates which, together with the so-called gas oil, were almost a drug on the market 25 years ago.

Some idea of the magnitude and growth of the production of kerosene oil is found in the records for 1906 and 1909. In the former year the total production of kerosene is estimated by the Standard Oil Company to have been 48,000,000 barrels or 2,016,-000,000 gallons; and, in 1909, 53,000,000 barrels or 2,226,000,000 gallons, an increase in 3 years of more than 10 per cent.

Pintsch Gas

Pintsch gas is so named after Julius Pintsch, of Germany, the founder of the great firm of that name.

Pintsch gas is made by the destructive distillation of petroleum or other mineral oil in retorts (cast iron or clay) externally and continuously heated, or in generators filled with fire-brick checker-work, internally and intermittently heated. The product is in great measure a fixed gas, principally methane (CH_4) and heavy hydrocarbons with a very small volume of hydrogen. The oil gas as so made, unlike water gas, is not diluted.

The Pintsch system was originally developed for the lighting of railway passenger cars. In the early days of railroading some trains were not run after dark, and in many cases where the trains were run through the night hours it was not considered necessary to furnish artificial illumination. The illuminants first employed were candles and oil lamps.

In 1866 experiments were begun in Germany in the lighting of railway carriages with coal gas. It happened that in the United States the Reading Railroad also began to light some of its cars with coal gas in the same year.

By reason of the limited space available on railroad cars for the storage of the illuminant, city gas was found to be too bulky, and this suggested that the gas should be of comparatively high candle-power and be compressed into a greatly reduced volume. This led Pintsch to turn his attention to gas made from coal oil and petroleum.

As compared with coal gas a double advantage was secured by the substitution of compressed oil gas for railroad lighting and similar service, for the oil gas, in addition to an initial illuminating power three or four times higher than that of coal gas, suffers a loss in illuminating power due to compression of only one-third to one-half of that of coal gas. This loss in compressing Pintsch gas to 10 atmospheres is only about 10 per cent.

The advantages of compressed oil gas so markedly apparent in its application to the lighting of railway passenger cars were in even greater degree found to be applicable to the lighting of buoys, beacons, stake lights and lightships. In the late seventies Pintsch turned his serious attention to the development of a system to satisfy the varying demands of lighthouse authorities and met with prompt success.

For the storage of compressed gas at the works Pintsch developed a process of welding by which were produced storage cylinders of large capacity free from seams or rivets. These seamless cylinders are now manufactured to a maximum size of 8 feet in diameter by 33 feet in length. For lighthouse work welded buoys were made of the several required shapes, the body of the buoy serving as a holder for the compressed gas. Difficult as was the welding of the storage cylinders, the welding of the buoy bodies was far more difficult. The application of this welding system to the manufacture of buoys was particularly useful, because by eliminating riveted joints there was obtained the necessary strength and capacity with the minimum of weight, and consequently the maximum of buoyancy.

Pintsch also devised a wind- and wave-proof lantern which demonstrated its ability to maintain a steady and constant light under the severest weather conditions.

In the use of compressed gas for car lighting, and still more for lighthouse service, it was necessary to develop a pressure regulator capable of receiving the gas at a pressure of from 150 pounds to 1 pound per square inch, and delivering it constantly to the burner supply pipe at such a reduced pressure as might be required for the most efficient operation of the particular burner employed. To meet this requirement Pintsch invented a regulator which, practically without change, has met successfully all the requirements of nearly 40 years of the most varied and exacting service.

As far as I know, and I had a very personal experience with this regulator from the latter part of the year 1881 to the end of 1884, no gas, compressed or uncompressed, is supplied to the point of ignition under more uniform pressure than the gas supplied by the Pintsch system. I lay particular stress on this point because I know that questions have frequently been raised as to the complete reliability of such an instrument for constant and accurate regulation within narrow limits of outlet pressure.

I will describe briefly a couple of tests which occurred under my own eye about the year 1883. The first was a test by the representatives of the United States Lighthouse Board of a Pintsch regulator and buoy lantern in competition with similar appliances of a rival system. The claim was made for the latter system that operating under 600 pounds pressure a decided advantage was secured by reason of the longer supply of light thus obtained from the one filling of the gas reservoir. Although the Pintsch governor was only tested and guaranteed for a pressure of 150 pounds, to meet the claims of the competitor, the Pintsch Company's representatives offered to subject this governor to the 600 pounds pressure. Upon examination it was found that the storage holder of the rival concern was charged only to 300 pounds instead of 600 pounds as claimed. U-water gauges were connected to the pipes connecting the governor outlets to the lanterns. The inlet pressures to both governors were first adjusted at 1 pound, and the corresponding outlet pressures as indicated by the U gauges were accurately observed and marked. By a quick movement of the hand the full pressure of 300 pounds was admitted to the inlet of each of the governors. In the case of the Pintsch governor the fluctuation of the governed pressure, as indicated by the U gauge, was found to be less than one-tenth of an inch of water and the flames were not affected; whereas in the other case the water was blown out of the U gauge and struck the ceiling of the room in which the test was being made, and the light was extinguished. In this test the lanterns were also subjected to conditions representing a hurricane, the wind effect being obtained by the use of an air blower and the washing of the waves by water delivered from a 2-inch hose under heavy pressure against all parts of the lanterns. The Pintsch lantern remained lighted while the other was extinguished.

The other case also served to show the reliability of the governor and the buoy lantern under extraordinarily severe conditions. Following a heavy storm it was reported that one of the buoys recently anchored in New York Harbor had been extinguished. With the Lighthouse Board's district inspector, I made a personal investigation. When we arrived at the buoy, from the tender it appeared that the light was extinguished. Determined that there should be no question as to the accuracy of the record I climbed into the cage surrounding the lantern of the buoy. Opening the lantern I found that the set-screw which regulates the size of the flames had been screwed down hard so that the amount of gas leaking by was only sufficient to produce flames practically non-luminous, with the result, even after the lantern was opened, that those on the lighthouse tender could not see the flames. That the record should not depend upon my word I demonstrated, by lighting a piece of paper at the flames, that the light was not extinguished. The delicacy of action of the governor and the efficiency of the lantern can be understood when I say that the flames were so small that after lighting the paper I extinguished them by fanning them with a single motion of my hand.

While the use of pressure regulators in connection with the distribution of city gas introduces unnecessary complications, in the case of such special service as that which the Pintsch system has to perform, which necessarily demands special appliances designed and constructed to operate with mathematical accuracy, no additional complication is introduced provided the regulator is completely dependable. Given a gas delivered at a pressure well above that required for maximum efficiency with any illuminating burner, an important economic advantage is secured by the use of a governor which can be relied upon to reduce this excessive pressure to any desired point. This is well illustrated in the application of the Pintsch system to mantle lighting, as later to be explained.

Between the years 1870 and 1880 the Pintsch system of lighting was introduced to a very considerable extent on the Prussian State lines.

Pintsch's first United States patents were taken out between the years 1870 and 1880.

In the year 1880 the Pintsch system was brought to the United States, being first applied in lighting the sound steamers of the Stonington Line and the cars of the connecting line of the New

York, Providence and Boston Railroad, now part of the New Haven system. The Pintsch plant for supplying the boats and cars was located at Stonington, Conn.

The next railroad to adopt the light was the Erie, the works for making and compressing the gas being built in the railroad's yards in Jersey City. Shortly thereafter a similar plant was built at Weehawken for the West Shore Railroad, and practically all of its passenger cars then being built were equipped for the new light.

At first the policy of the United States Pintsch Company was to induce each railroad adopting the system to own and operate its own gas works, one or more. This would have led to unnecessary multiplication of gas works throughout the country. The policy was persisted in for a number of years, and in this is to be found the reason why the system made but little progress in the United States during the first years of the American company's existence. It was not until a new element came into control of the United States Pintsch Company that this policy was abandoned and more rapid progress made, the company undertaking the building of gas works and the supply of compressed oil gas to the railroads adopting the system. While now some of the railroads own and operate plants built for them by the company, the Pintsch Company owns and operates works of its own throughout the United States, Canada and Mexico, in many cases supplying several roads from the same plant. In a number of cities Pintsch gas is manufactured and distributed to the railroads by the local gas company operating in partnership with the Pintsch Company and the railroads served.

The Pintsch system is in use practically throughout the civilized world. Up to date about 180,000 cars in all are equipped for Pintsch light.

Up to April 30, 1909, there were in service in the following countries, namely, Great Britain, Germany, Holland, Belgium, France, Portugal, Denmark, Russia, Tunis, Sweden, Austria, Italy, United States, Brazil, Argentine Republic, Uruguay, Egypt, India, South Africa, Canada, Australia, New Zealand, Algiers, Spain, Japan and China, buoys, 1947; beacons and stake lights, 485; lightships, 96; these being supplied from 77 charging stations.

A later return, covering the lighthouse service for the United States and Canada, shows that on August 10, 1910, the number

of buoys in service in these two countries was 461, an increase of 30 in the 15 months.

Up to June 1, 1910, there were in the United States, Canada and Mexico 93 Pintsch gas works, supplying compressed gas to 360 railway stations. In the same territory, up to January 1, 1910, the number of cars equipped for the Pintsch system was 35,137.

During the last few years the Pintsch system has been further developed to secure the additional advantages to be obtained through the use of incandescent mantle burners. Up to date there are mantle lamps installed in railway cars as follows: France, about 95,000; Great Britain, about 61,000; other European countries, about 152,000; United States, Canada and Mexico, about 80,000; total, about 388,000. These figures represent mantle-lamp equipment for about 55,400 cars.

Pintsch gas, as has been stated, is obtained by the destructive distillation of oil. In the early days of the system oil produced by the distillation of coal or shale was used. Of late years crude petroleum oil and its distillates have been employed, market conditions controlling the choice. The crude oil can be satisfactorily employed and was at one time largely used. To-day market conditions generally lead to the use of a distillate.

At first, and until recent years, the gas was manufactured only in cast-iron retorts externally heated. Much of the gas is still so made. Two retorts are set in each "bench" or furnace, the two retorts being so connected at their back ends that the gas passes from one to the other. The oil is introduced at the front of the upper retort and falls upon a removable sheet-iron tray which collects most of the carbonized oil. The gas and vapor produced in the upper retort pass down to the back of the lower retort, and so through to the front of the bench, passing by a decension pipe to the hydraulic main located below the floor of the house. Issuing from the hydraulic main the gas and vapor pass through a dry scrubber, condenser, purifiers and station meter, and are collected in the low-pressure storage holder. From the storage holder the gas is drawn by a compressor, compressed into one or more of the welded cylinders before described, and is then ready for distribution through the high-pressure pipes to the cars or transport holders. All necessary precautions are taken to trap the liquid hydrocarbon thrown down by the process of compression, the object

being to obtain a thoroughly dry gas, which result is secured to a remarkable degree.

The early German practice limited the compression between 8 and 10 atmospheres. The more recent practice, especially in the United States, is between 12 and 14 atmospheres.

Particularly in connection with the larger plants, clay retorts, as used in coal-gas manufacture, came into use. This change, by reason of the porosity of the clay retorts, has made necessary the employment of exhausters to draw the gas from the retorts and push it on through the other parts of the plant to the storage holder.

When the gas is distilled in clay retorts the distillation is completed in a single retort, the oil being introduced through a wrought-iron pipe carried through the front of the retort, extending nearly its entire length and open at the end. The oil, gas and vapor issue from the open end of the pipe and return through the retort to the front. The gas and vapor issue from the front of the retort and pass by an ascension pipe to the hydraulic main located on the top of the bench, and from there, as before described, to the storage holder.

Some years ago experiments were undertaken to determine if greater economy could be secured by distilling the oil in generators internally fired. This is necessarily an intermittent process and so is markedly differentiated from the continuous retort process.

The generator consists of a steel shell 6 feet in diameter and about 12 feet in height. It is lined with fire-brick and the interior is divided into two compartments, a smaller lower compartment which serves as a combustion chamber, and a larger upper compartment which is filled with fire-brick checker-work nearly up to the top of the shell; this upper chamber terminates in a cone, upon the top of which is a stack valve.

The tar, obtained as a by-product from the distillation, is used as fuel. This is injected into the combustion chamber below the checker-work by means of a liquid-fuel burner. A mechanical blower produces the necessary forced draft.

As soon as the generator has been "blown" to its proper working temperature the tar fuel, steam and air are shut off and the stack valve is closed. Gas oil under pressure is then injected through three oil nozzles located in the top of the generator and the finely divided oil is thrown upon the checker brick. The oil vapor so

formed passes down through the heated checker bricks and is so decomposed, the gas produced finally issuing from the generator through the take-off pipe located in the side of the combustion chamber.

The cycle is divided into a heating period ("blow") of about 5 minutes, and a gas-making period ("run") of from 6 to 8 minutes.

The rate of flow of oil is regulated by the so-called trowel test which the gas maker applies at short intervals. This test consists in permitting a fine jet of the hot gas to impinge upon the polished blade of a mason's trowel, the figure made upon the trowel by the condensed tar indicating to the practiced eye the amount of condensable vapor in the gas. With care in operation the gas is obtained of quite uniform quality in spite of the gradually decreasing temperature of the generator.

About 1500 feet of the gas are made per "run."

The gas after leaving the generator is dry scrubbed and cooled, and is then collected in a "relief" holder. From the holder it is drawn by the compressor through the purifiers and station meter, and then compressed into the high-pressure storage holders at a pressure of about 14 atmospheres.

It is found that by this method of intermittent distillation in internally fired generators a gas can be obtained about 10 per cent higher in candle-power than by the retort process, with the attendant advantages of largely reduced floor space, reduced cost of construction, and lower manufacturing cost due to economy in fuel, labor and repairs.

In order to simplify the apparatus and reduce the investment at stations where the output is small, a still later development is the generation of the gas under the pressure required for delivery. (See Fig. 1.)

To withstand this heavy pressure, the generator shell is constructed of heavy steel plates. The shell is divided as follows: At the bottom, a combustion chamber; above, a chamber filled with fire-brick checker-work; above this, a space for the oil sprays; and above this, another chamber filled with checker-work.

The "blow" and "run" occur as in the low-pressure generator. In order, however, to check the rapid decomposition of the oil, which would otherwise occur when operating under heavy pressure, steam is injected with the oil into the generator. The steam so

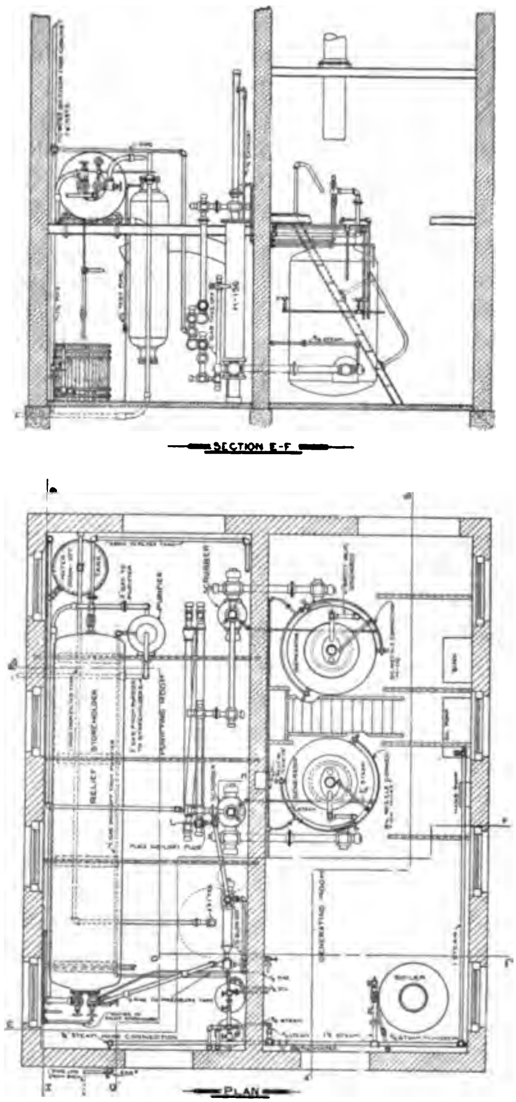

FIG. 1.—Pintsch Gas High-Pressure Generator Plant.

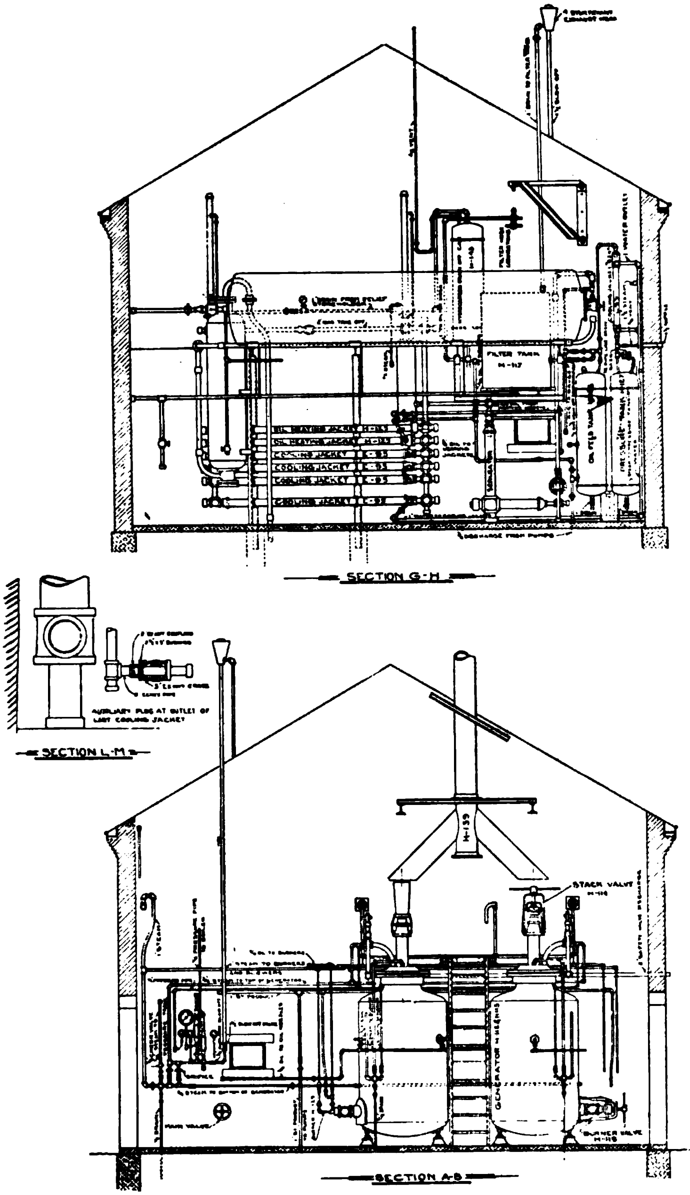

FIG. 1a.—Pintsch Gas High-Pressure Generator Plant.

used acts as a carrier and protector for the oil vapor and gas, and does not react with the carbon of the oil to produce water gas, the temperature of the generator being too low for this reaction.

The steam enters the generator at the top, being superheated in passing down through the upper checker-work. Coming to the

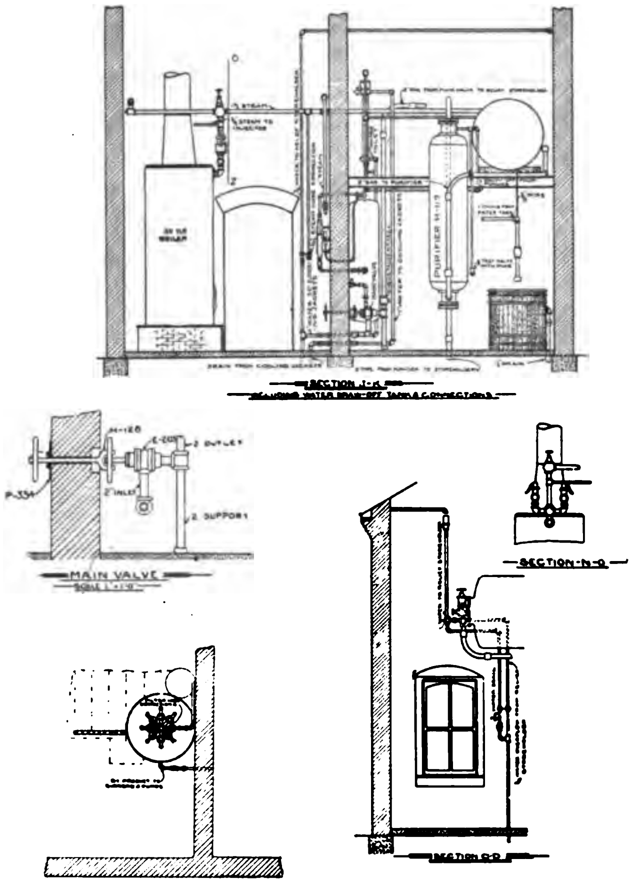

FIG. 1b.—Pintsch Gas High-Pressure Generator Plant.

intermediate chamber it meets and mingles with the finely divided oil, and then steam and oil vapor pass down through the second checker-work wherein the oil vapor is decomposed. The gas and superheated steam finally leave the bottom of the generator through the take-off pipe in the side of the combustion chamber. The gas

and highly superheated steam are then dry scrubbed and cooled, and the gas, tar and water are charged into the first storeholder under a pressure of about 14 atmospheres. Passing from the first storeholder the gas is purified under pressure and is then stored in other high-pressure storeholders.

Before the next "blow" the gas and oil vapor which remain in the generator under pressure are displaced by means of steam at sufficient pressure, being thus forced through the scrubbing and cooling devices and into the storeholders.

This high-pressure plant is more simple and compact because the low-pressure gas holder and compressing apparatus are not required.

Three of these high-pressure generator installations have been put into operation, and one of these has been operating satisfactorily for 2 years; three more are now in process of construction.

In both low- and high-pressure systems the generators are operated at a temperature of about 1200° F.

The average of analyses of 25 samples of compressed Pintsch gas was as follows, and furnishes a representative indication of its composition:

Methane CH_4	60%
Heavy illuminants:	
Benzene C_6H_6; Propylene C_3H_6; Ethylene C_2H_4, etc.	35
CO	.5
Hydrogen	4.5
	100.0

Specific gravity .80 to .85.

Ignition temperature, determined by Milton L. Hersey, chemist and chief engineer of tests of Canadian Pacific Railway, made at McGill University 1562° F. or 850° C.

Explosive limit between about 4 per cent and 10 per cent of the gas.

The horizontal candle-power of the compressed gas, tested in open flat-flame burner sufficiently small to avoid smoking and calculated to the 5 feet per hour consumption, is about 40. By reason of the necessarily small rate of consumption this does not furnish a reliable indication of the candle-power. The spherical illuminating power of the lamps, naked flame and mantle, as later to be stated, are the values to be considered for purposes of comparison.

Most of the Pintsch gas is used for the lighting of railroad cars. While a relatively small amount is used in lighting buoys, beacons, etc., the service performed is one of commanding importance. In the early days steamers and ferry boats were satisfactorily lighted by this system. Many of the ferry boats plying in New York Harbor were at one time lighted by coal gas, uncompressed or compressed. In some cases these methods were superseded by the Pintsch system. The advance in the art of electric lighting, coupled with the special adaptability of electric lighting to the illumination of vessels equipped for steam power, led naturally to the replacement of compressed gas by the electric light.

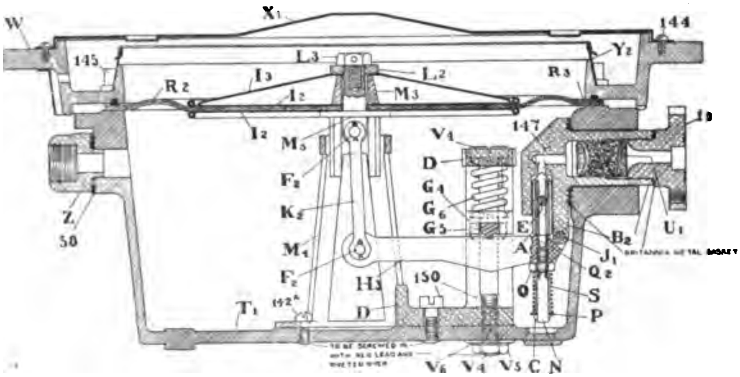

Fig. 2.—Pintsch Gas Regulator.

The Pintsch regulator deserves more than a passing notice. (See Fig. 2.) The essential parts of the regulator are a needle valve of special form and a large diaphragm made of leather so treated as to be gas proof and extremely flexible. The diaphragm is subjected only to the reduced or regulated pressure and controls the movement of the valve through a lever of such proportions that the pressure of the valve against its seat is 11 times the total pressure against the diaphragm. A pair of springs acting on the lever through a knife edge oppose the pull of the diaphragm and can be regulated so as to give the required outlet pressure. The needle valve, so controlled, is relied upon to exclude the high pressure from the interior of the regulator, no auxiliary valve being employed for that purpose when the lamps are shut off.

For the illumination of railroad cars many forms of naked-flame lamps have been employed. These have all been designed to meet

the exacting requirements necessarily involved in the lighting of cars running at varying speeds, subject to abrupt stops, so ventilated that the lamps are required to resist strong air draughts, and under the care of trainmen who cannot be relied upon to give the lamps expert attention.

As this is one of a number of lectures on illuminating engineering it is in order that I should call particular attention to the fact that the engineers of the Pintsch Companies here and abroad have recognized constantly that they were required to solve their problems from the standpoint of the engineer of illumination. Not only has the effort been to secure the greatest amount of light from a minimum of material and at a minimum cost, but the effort has been to distribute this light so as best to serve the travelling public. It has always been recognized that an important element in the problem was to secure an effect which would be pleasant and restful to the eye. All the problems involved have been under discussion and subject to experimentation constantly. It was recognized that the first step was to obtain a steady flame, free from flicker, and that this must be secured through the design of a draught-proof lamp and a pressure regulator at once sensitive and reliable.

I know that some hold that illuminating engineering was not the subject of scientific study by gas engineers until the electric light engineers led the way. I am inclined to think that some of our electric light associates in the Illuminating Engineering Society are of this number. Many facts in regard to gas engineering practice could be cited against this proposition. In addition to the record made by the Pintsch engineers, let me refer to one example, which is notable in this connection. Some few years ago, at a meeting of a committee of our Society, I learned that the electrical engineers present were of the opinion that a notable advance in the science of illumination was made when rooms were first illuminated by light reflected from sources hidden from the eye, and that this advance was to be credited to the electric light engineers. I then described the lighting of the Liverpool Philharmonic Hall by naked gas flames placed so as to be hidden from view by the plaster cornice, the light being reflected down into the hall from the curved surface of the ceiling. This installation was made 50 years before I first saw it, which was over 10 years ago.

I trust I may be pardoned for this little digression, and especially by my electric light associates.

Figure 3 shows a flat-flame four-burner railroad car lamp. It is here to be borne in mind that the methods of hanging and the design of the body of the lamp have been varied to meet practical conditions and the demands, sometimes artistic and sometimes not, of the railroads' managers. In this lamp the air supply to the burners passes through the upper portion of the body and so into the cylinder enclosing the four chimneys, down into the lower portion of the lamp and so into the globe, where it reaches the flames. The products of combustion go up past the central re-

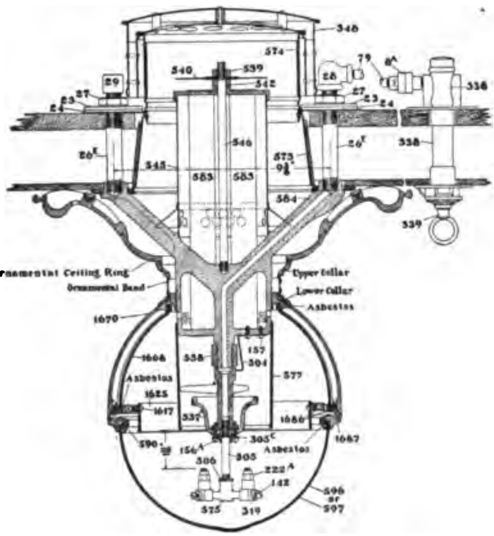

FIG. 3.—Four-Burner Flat-Flame Railroad Car Lamp

flector, and so on up through the chimneys, some of the sensible heat of the products of combustion being transferred to the incoming air.

The four burners together consume about 3¼ feet of gas an hour, and give 30 to 35 mean hemispherical (lower) candle-power.

Of recent years the Pintsch Companies have devoted much attention to the application of incandescent mantles to car lighting and buoy lighting. Experiments with vertical mantles were not successful, by reason of frequent breakages. After the trial of many devices to reduce the effect of shock the engineers of the United States Company solved the problem by means of a strong inverted mantle *rigidly* fixed to the burner. To secure increased

strength these mantles are made heavier than the ordinary mantle, and to compensate for the loss in illuminating power due to this increase in mass the gas is supplied to the burners at a pressure of 2 pounds. This advantage is secured by the use of a compressed gas controlled by a reliable governor. It is a rather remarkable fact that the lamps are not provided with means of adjustment. The gas orifices and air inlets are drilled to standard sizes, and,

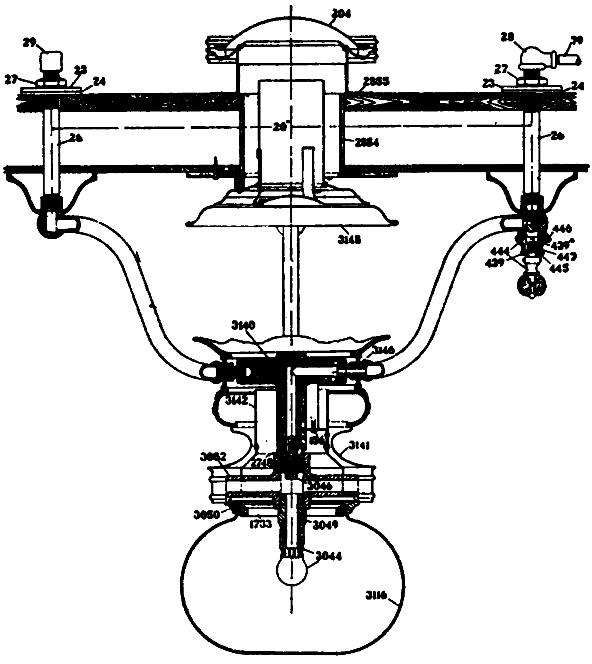

FIG. 4.—Single Mantle Car Lamp.

having passed the calibration tests, the lamps are erected as turned out from the factory.

These mantle burners consume 2 feet of gas an hour and give (the mantles alone) 90 to 100 *horizontal* candle-power without the aid of reflectors. As arranged in the car lamp, they give a *mean hemispherical* candle-power of 90 to 100. Comparing with the flat-flame lamps already described, the lighting effect is about 4 to 1, and with the same gas storage capacity the length of period between fillings is practically increased 60 per cent.

These inverted mantles as now used have established a satisfactory life record. Some little time ago a careful observation was made of their service on 25 steam railway cars engaged in New York suburban traffic. These cars were equipped with 125 lamps. The cars were handled in the regular way by the trainmen, who were not informed that the lamps were under special observation. The Pintsch employees, however, renewed all broken mantles so that an accurate record of the mantles used might be obtained. The result of this test for the 125 lamps was an average mantle

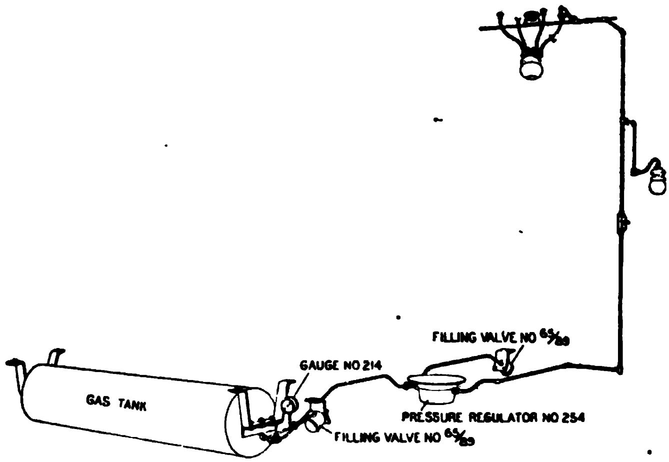

FIG. 5.—Car Equipment for Pintsch Lighting.

life of 376 days. This shows a notable improvement even over the old inverted mantle as first made.

The construction of the lamp is shown in Fig. 4. The regulated gas at 2 pounds pressure is admitted through fitting No. 3146, and passes down to a strainer of peculiar construction placed in the vertical channel. The gas issuing therefrom is met by the air pulled in at the sides by the gas, and the gas and air mixture then passes down unobstructed to the burner, which consists of a metal disc accurately drilled with seven orifices.

Fig. 5 shows car equipment for Pintsch lighting; Fig. 6 is an interior view of a railway coach lighted with mantle lamps, and Fig. 7 is an illumination diagram for such a coach.

I cannot conclude this section of my lecture without describing, at least briefly, the Pintsch buoy, a very beautiful example of

specialized engineering akin to illuminating engineering. (See Fig. 8.) The buoy body is a seamless welded-steel shell designed and constructed to withstand the high pressure of the gas stored therein, and to afford ample buoyancy for the support of the anchor chain, lantern and other parts. The buoy bodies are made in

FIG. 6.—Interior View of Coach with Mantle Lamps.

different shapes to meet varying conditions as to depth of water, anchorage, tideways, etc. A suitable tower surrounded by a cage supports and protects the lantern and carries a platform to afford a footing for the attendant when lighting or adjusting the flames. The lantern is designed and constructed to protect the light from

rain, waves and wind under the severest possible conditions to be found close to the surface of the sea. The base of the lantern forms the case for the pressure governor.

In the original lantern the burner was placed inside a Fresnel dioptric fixed-light lens which, by bending the light rays, confined them approximately between two horizontal planes, thus increasing

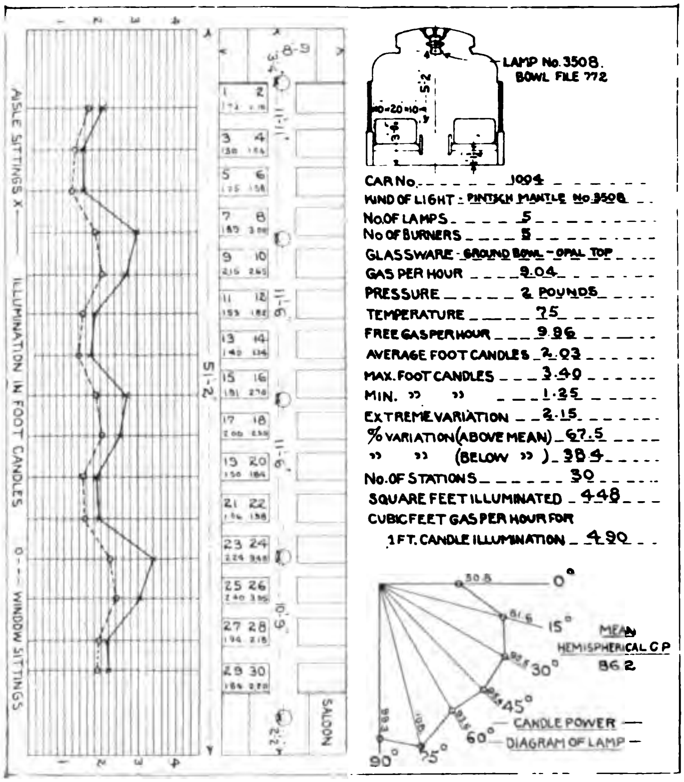

Fig. 7.—Illumination Diagram for Coach with Mantle Lamps.

the power and range of the light. Some of the lanterns thus equipped are still in use. In order to give the light a specific characteristic and at the same time reduce the gas consumption and so increase the interval between gas chargings, a further improvement was made by the addition of a flashing mechanism. This is a simple and reliable device which controls the flow of gas to the burner so that the gas is ignited and extinguished at intervals, the

lengths of which are predetermined to meet the particular conditions of each case. This automatic mechanism is enclosed in a chamber located immediately above the governor, and is actuated by the gas flowing through this chamber on its way from the governor to the flash-light burner, which is ignited by a pilot light burning continuously and receiving its gas supply direct from the governor.

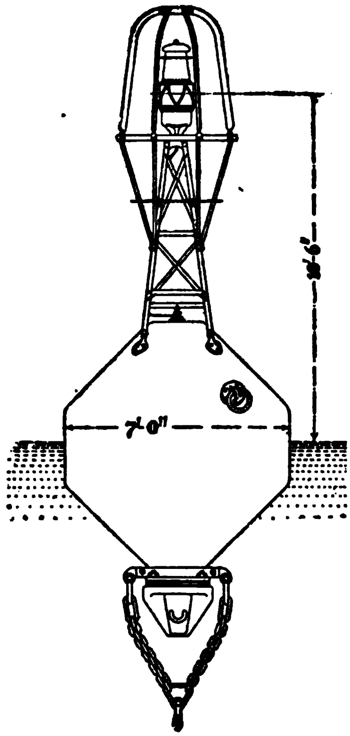

FIG. 8.—Pintsch Buoy.

The relative periodicity of light and darkness can be varied by the adjustment of the mechanism to meet varying requirements. The standard adjustment gives periods of equal lengths, usually 5 seconds or 10 seconds each. If desired the periods can be made non-uniform.

The latest form of this mechanism provides for the buoy being used either as a fixed or flash light, as required for any location; all the buoys as now built and supplied are so equipped. Nearly

all the buoys now in use are equipped with the flash-light mechanism, and most of these are of the convertible type.

As the fixed-light lens permits the rays to radiate horizontally through 360 degrees, to still further increase the power and range of the buoy lights a "bull's-eye" or flash lens can be employed instead of the flashing mechanism just described. If desired, a series of these lenses can be grouped in a circle around the light source. That the light may be visible at all points in the horizon the bull's-eye lens, or series of lenses, must be revolved. This is effected by a motor driven by the gas flowing to the burner. This lens arrangement delivers a light at least 20 times as powerful as that from the fixed-light lens.

An additional advantage is that the characteristic of the buoy light can be further determined by the design and the relative positions of the lenses of the series. There are comparatively few of the revolving lenses in service.

Until recently flat-flame burners were used exclusively in the Pintsch buoys, but mantle burners are now displacing the flat flames. The older lanterns are being remodeled for mantle burners, and all new lanterns are of this type. (See Fig. 9.)

As compared with the flat flame the mantle burner gives a candle-power three times as great, and its intrinsic brilliancy is ten times as great, resulting in greatly increased power for the same consumption of gas. The flat-flame burners are made for different rates of consumption, while the mantle burners are made for one rate only.

Bells operating either above or below the surface of the water and actuated by the flow of gas supplying the burner are in some cases attached to these buoys.

With one gas charge these buoys will run from 55 to 528 days; the size of the buoy body, whether flat-flame or mantle burner, whether fixed or flash light, and if flat flame, the size of burners, determining the number of days.

Stationary beacons and light ships are also equipped for and operated with Pintsch gas.

Gas under a pressure of 100 atmospheres is now being used extensively for this marine work. For beacons and light ships it is burned direct from the cylinders in which the gas is conveyed. In the case of buoys the high-pressure cylinders obviate the necessity for large storage holders and compressors on the supply tender,

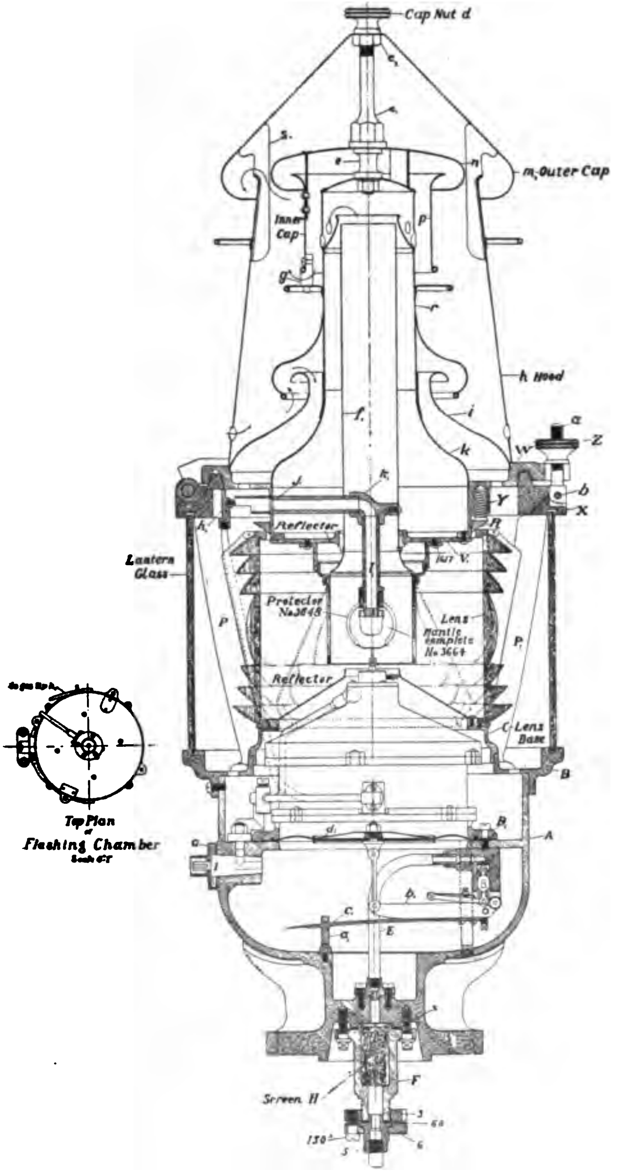

FIG. 9.—Pintsch Buoy Lantern with Mantle Burner.

the buoys being charged direct up to 10 atmospheres from the 100-atmosphere cylinders.

It is found that about 133 volumes of the gas can be stored under a pressure of 100 atmospheres, and that little or no additional loss in candle-power is suffered in carrying the compression from 14 to 100 atmospheres. There is an additional deposit of liquid hydrocarbon, as indicated by the increased storage volume, but if the outlet pipe is sealed in this liquid the liquid revaporizes, and at the reduced pressure of 14 atmospheres and below it is carried through the appliances to the burner practically as a dry gas.

Let me conclude by pointing out two features of the Pintsch system of great practical advantage to its patrons.

In connection with the filling of the cars it is important that the amount of gas delivered to each car should be readily ascertainable for record. It is even more important that the attendant should be able to tell by inspection at any time how many hours of lighting are provided for by the gas in the cylinder. Both of these requirements are met by making the cylinders of standard sizes, the cubical contents in feet being marked and recorded. A high-pressure gauge showing the pressure in atmospheres is attached at each car-filling valve. The simple calculation of multiplying the gauge reading by the capacity of the cylinder gives the available volume of gas contained.

Another important feature is that throughout the territory covered by the United States Pintsch Company all parts of machinery and all fittings are interchangeable. The design of the smallest and apparently most insignificant part has been carefully considered. The engineers have from the first recognized that they were offering to perform a special service involving many difficulties. As a result, a system has been developed that provides for the supplying of Pintsch gas to any railroad car equipped with Pintsch standardized appliances, no matter how far that car may be from its home territory, provided it is within reach of any one of the 93 gas works or any one of the 360 Pintsch gas-supplied railway stations located in the United States, Canada or Mexico.

Carburetted-Air Gas

Carburetted-air gas consists of atmospheric air to which hydrocarbon vapor has been added, the proportions of air and vapor varying with the process employed.

The application of carburetted-air gas as an illuminating and heating agent to meet certain special conditions has been an industry for about 40 years. As a source of energy in the internal combustion engine its use has been of late greatly increased and extended.

Carburetted-air gas machines can be grouped in two classes, those operated without heat and those operated with heat. Those of the former group have been more generally employed, especially where the principal service has been lighting. In operating with cold air it is necessary to use refined highly volatile gasoline; but if steam or other heat source is employed to assist evaporation, the somewhat less volatile and less expensive naphthas are used.

Carburetted-air gas differs fundamentally from coal gas, water gas or oil gas through the fact that whereas in the process of mixing the liquid hydrocarbon is vaporized it is not changed chemically, while in the case of the other three gases the manufacturing process to which the coal or oil is subjected converts the hydrocarbon into fixed gases in major proportion and certain vapors in minor proportion.

In the distillation of crude petroleum, as the temperature of the still rises, the several distillates are driven off successively according to the following approximate classification:

Readings of Baumé Hydrometer	Corresponding Specific Gravity	Trade classification
90° and above	0.6363 and below	Rhigolene & cymogene
90° to 80°	0.6363 to 0.6667	Gasoline
80° to 70°	0.6667 to 0.7000	Light naphtha
70° to 60°	0.7000 to 0.7368	Heavy naphtha

Following these distillates come the kerosenes, lubricating oils, gas oil, solid hydrocarbons, tars and solid carbons or hydrocarbons.

While refined gasoline of 90° B. (sp. gr., .6363) is obtainable in this country, the price and the extra difficulty in holding it against evaporation have operated to prevent the development of a wide market for this grade.

Refined gasoline lighter than 86° B. (sp. gr., .6481) is not generally obtainable in this country. This distillate consists mainly of hexane (C_6H_{14}) and pentane (C_5H_{12}), with some still lighter and some heavier hydrocarbons. It should evaporate under conditions of use without giving off at first an excess volume of light vapors or leaving unvaporized heavy residues. A distillate capable

of meeting these conditions can be obtained only by repeated distillations in the refinery to isolate in the gasoline those closely related hydrocarbons which will evaporate in approximately the same volumes under the same conditions. The refining process must also provide for the removal of all traces of tar which otherwise would deposit in the smaller pipes, gum the floats and clog the burners. For the making of air gas the more general practice has been to use a gasoline of about 84° B. (sp. gr., .6542). While this distillate leaves unvaporized a little residue, the amount is small, and as a rule does not have to be pumped out oftener than every 6 to 12 months. It is interesting to note that the residue is about 63° B. (sp. gr., .7254). The nomenclature which developed to identify the distillates of petroleum in many cases is based only upon a commercial or industrial suggestion. As the names given to several of these distillates have been the occasion for considerable confusion, a few words of explanation may not be out of place.

When these lighter distillates from petroleum were first obtained uses for them in the arts were still to be found. In manufacturing kerosene, for which there was a ready market, the refiners were embarrassed to find storage for these distillates, produced as by-products, and for which there was little or no market. At that time benzene—a hydrocarbon having the chemical formula C_6H_6, obtained principally from the distillations of coal-tar—possessed a considerable value in the industries as a solvent for fats and greases and an enricher for gas. It soon became clear that some of the lighter distillates of petroleum could be used as a substitute in part for benz*e*ne, and thus a commercial reason was furnished for designating these distillates by the name benz*i*ne. In the same way other distillates of coal-tar, known as light and heavy naphthas, had their names pre-empted for other petroleum distillates. As the nomenclature thus developed fails to meet the requirements of a technical terminology the result naturally has been a most embarrassing confusion in technical and industrial literature. As an example, there are uses for benzene and coal-tar naphthas for which the petroleum distillates cannot be substituted; hence the need to be sure whether the substance under consideration is benzine or benzene in the first case, or naphtha or petroleum "naphtha" in the second case. Another feature of commercial practice which has led to confusion is that of designating the specific gravity of petroleum distillates by the Baumé hydrometer readings, even to

the extent in some cases of calling that reading the specific gravity. This is all the more unfortunate for the reason that in the upper part of the scale as the Baumé reading increases the distillate is of a lighter specific gravity, and in the lower part of the scale as the Baumé reading decreases the distillate is of a heavier specific gravity, the Baumé reading of 70° indicating a specific gravity of .70.

An additional complication arises from the fact that the Baumé scale for *liquids lighter than water* is calculated on more than one formula, and therefore the tables used in converting Baumé degrees to specific gravity do not always agree. The values here given are calculated on the formula sp. gr. equals $\frac{140}{130 + \text{Baumé reading}}$ which is the American standard. Another formula more often followed in English books, is $\frac{146.3}{146.3 + \text{Baumé reading}}$. Unfortunately, the tables are frequently given without the formula and the unwary may be deceived. Some authorities are careful to state in the title of the table, "American Standard." In the majority of books of reference the tables do not go above 80° B., and in some the tables are even more limited. For these reasons for American practice it is convenient to remember the formula sp. gr. equals $\frac{140}{130 + \text{Baumé reading}}$.

The volume of gasoline vapor that can be carried by a given quantity of air depends upon the temperature, the pressure remaining constant. The ability of air to take up and hold in suspension gasoline vapors increases very rapidly with the increase in temperature. Professor Leslie says in this connection that while the temperature itself advances uniformly in arithmetical progression the increased dissolving power thus communicated to the air advances with the accelerating rapidity of a geometrical progression.

While experiments that have been made to test this theory have not agreed in confirming its truth, they suggest that it may be at least approximately true.

Sir Boverton Redwood states with regard to 86° B. (sp. gr., .6481) gasoline that

100 volumes of air at 32° F. will retain 10.7 per cent of vapor, (9.7 per cent of the mixture).

100 volumes of air at 50° F. will retain 17.5 per cent of vapor, (14.9 per cent of the mixture).

100 volumes of air at 68° F. will retain 27 per cent of vapor, (21.3 per cent of the mixture).

In this connection Redwood goes on to say that "air charged with 735 grains of gasoline per cubic foot has been found to possess an illuminating power of 16.5 candles when consumed at the rate of 3½ cubic feet an hour in a 15-hole Argand burner."

If we assume the gasoline vapor to have a specific gravity of 3., it follows that the mixture has 31½ per cent of gasoline vapor by volume.

Redwood goes on further to describe a series of experiments, which he carried on with the assistance of Mr. Blunderstone, to determine "the manner in which crude petroleum and certain volatile petroleum-distillates evaporate when subjected to a current of dry air. . . . In these experiments, dry air was caused to bubble slowly through the liquid in a series of graduated tubes maintained at a constant temperature. . . . A set of determinations being made at temperatures of 40°, 60°, 80° and 100° F."

At 60° three determinations were made with gasoline of a sp. gr. of .639, 44.7 c. c. of the liquid being used. In the first, 0.9 liter of air was passed through the six tubes; in the second, 2.15 liters, and in the third, 3.55 liters. The first gave a total evaporation of .66 volume of liquid to 100 volumes of air; the second gave .59 and the third .51 volume.

It is thus seen that the relatively small amount of air took up the largest amount of gasoline. The result of the first test, if calculated, shows that the mixture contained 53 per cent by volume of the gasoline vapor—certainly an extraordinary result. The probabilities are, at least in this last series of experiments, that the small quantity of air slowly bubbling through the liquid in six small streams resulted in a selective evaporation. If so, this does not truly represent the result from a liquid of .639 sp. gr. Certainly, we are not warranted in believing that any such percentages of gasoline can be carried in air-gas practice as are indicated in the two cases last quoted.

The limits between which gasoline vapor and air form an explosive mixture are 2 per cent of vapor with 98 per cent of air and 5 per cent of vapor with 95 per cent of air by volume. This fact furnishes a reason for dividing carburetted-air gas into two classes:

First, that in which the proportion of gasoline vapor to air is less than 2 per cent; and, second, that in which the proportion of gasoline vapor to air is more than 5 per cent.

The former presents some very interesting features. A carburetted-air gas containing 1½ per cent of gasoline vapor is low in heating value, is non-explosive, is non-asphyxiating, and yet, when used with a Welsbach mantle, furnishes a satisfactory light. It would appear that such a gas has much to recommend it. This class of air gas has been adopted in England to a considerable extent for lighting country estates, audience halls, summer hotels, and the like. As yet it has received little recognition in this country. A company is now presenting its claims for recognition.

The specific gravity of the vapor of gasoline, as now generally used for air gas, is about 3.

The calorific value of gasoline is variously quoted. In this connection it is to be remembered that "gasoline" is not a substance of constant chemical composition. Furthermore, the statements do not always show whether the value quoted is gross or net heating value. The United States Geological Survey gives 19,200 B. t. u. per pound as the net value of gasoline of .71 to .73 specific gravity. Bulletin No. 191 of the United States Department of Agriculture, on the authority of Lucke & Woodward, gives 21,120 gross, 19,660 net, B. t. u. per pound.

Redwood, in discussing vapor tensions, says:

"Salleron & Urbain give also the following as the determined vapor-pressures (vapor-tensions) of petroleum products of various densities."

He then goes on to say that the values given are "founded on a belief not in all cases correct."

This table, so rather guardedly quoted by Redwood, gives as the vapor tension of distillate of sp. gr. .65 (B. 85.38), 2110 mm. of water. This can be accepted at least as approximately correct, and would then show that air would be saturated when 20.42 per cent by volume of gasoline was present.

In this country the use of carburetted air has been confined for many years to machines that produce a mixture containing over 5 per cent of gasoline vapor, and it has been the practice to use 5½ to 6½ gallons of gasoline to 1000 feet of the mixture, the content of gasoline vapor then showing a wide margin of safety above the 5 per cent explosive limit. A 5½-gallon gas burned in an Argand burner, gives from 15 to 16 candle-power, it contains about

$13\frac{1}{4}$ per cent gasoline vapor, and its specific gravity is about 1.26. The specific gravity of the mixture is important; for being heavier than air, in case of leak, not possessing the tendency to rise, it is less rapidly dissipated by the ordinary means of ventilation. This necessitates increased precautions against explosion and asphyxiation. Such a gas cannot be subjected to a temperature below 43° F. without depositing gasoline in the pipes; therefore, it must be protected against cold either by wrapping the pipes or by external heat. This gas will have a calorific value of about 570 B. t. u. per foot, and therefore can be employed to advantage for lighting (especially by mantles) and heating.

Four principal systems, the first substituting hydrogen for air, are used in the application of gasoline vapor to gas making, and these are as follows:

1. Although not an air-gas system, it may be convenient to mention here, by reason of similarity of method, the process of forcing manufactured hydrogen gas over or through gasoline by which the hydrogen, which has no illuminating value of its own, becomes saturated with the rich hydrocarbon vapors. This mixture has a high heating value; and especially when used with the incandescent mantle, a high illuminating value. This system is seldom found in general practice and is principally used in metallurgical laboratories.

2. The employment of devices by means of which a current of air is forced over or through a body of gasoline or some porous or fibrous material saturated or impregnated with gasoline, by which means the air becomes carburetted with the hydrocarbon vapors to such an extent that the mixture can be used advantageously for illuminating and heating purposes. This method is called the cold-air process, and is the one most used in small private installations and town plants.

Fig. 10 shows such an installation. It consists of a blower "A," carbureter "L" and mixer "M." The blower, operated by suspended weights, as shown in the drawing, or water power, takes in air and forces part through the carbureter and part into the mixer.

Fig. 11 shows a sectional view of a box-type carbureter, the kind generally used in plants of moderate size. It is a flat, rectangular box made of sheet metal, having partitions running longitudinally and parallel to each other through the box, but leaving a connect-

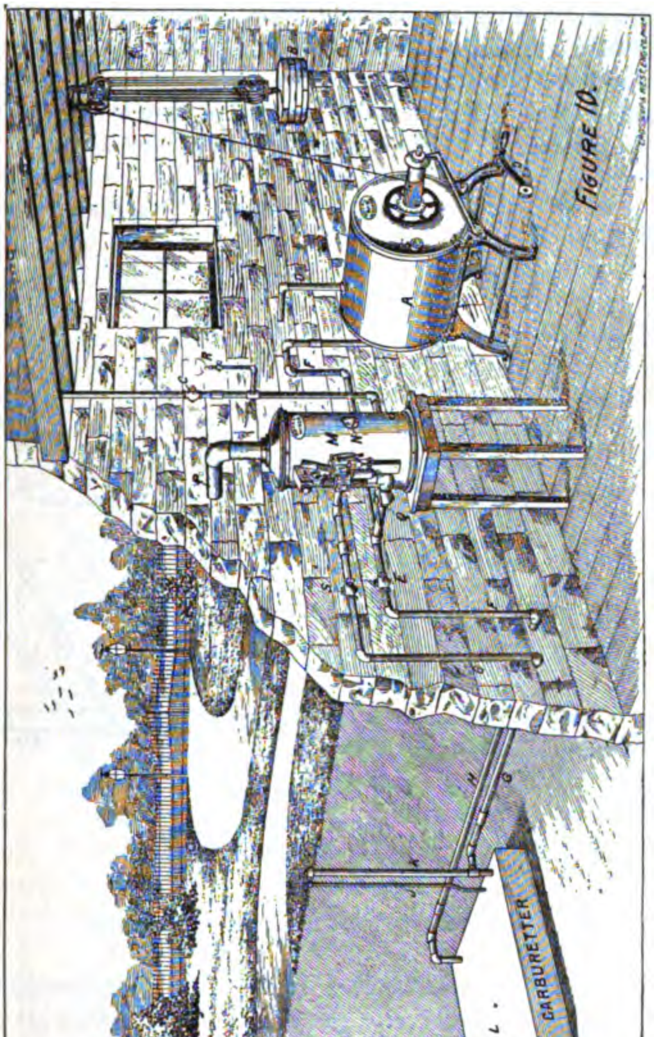

Fig. 10.

ing opening between each two adjacent compartments sequentially at alternate ends. In these compartments are hung or stretched, as shown, strips of Canton flannel. There is an opening for filling, an inlet for air from the blower at one end, and at the other end an outlet for the carburetted air. The carbureter is about 15 inches deep but is filled with gasoline to a depth of only 6 inches. It is buried in the ground. The air entering through the top at one end

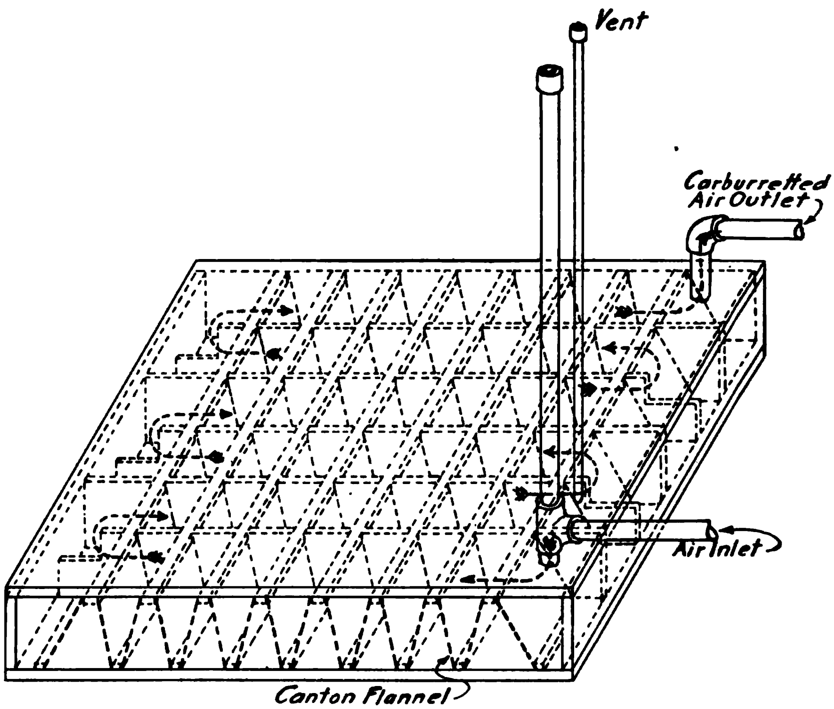

FIG. 11.—Carbureter, 50-Light Air Gas Machine.

traverses all the passages, flowing through the flannel which, by capillarity, is kept wetted with gasoline; the carburetted air then passing on to the mixer. The box must be of sufficient size to permit a very slow movement of the air and the recovery from the surrounding earth of the heat rendered latent by the evaporation of the gasoline.

As stated before, commercially refined gasoline is a mixture of several hydrocarbons, though largely composed of hexane and

pentane. Under the conditions of slow evaporation here presented, there is a selective evaporation, the lower boiling fractions going off in large volumes first, gradually decreasing in volume as the gravity of the remaining gasoline increases, until finally a minimum permissible candle-power is reached, when the carbureter must be recharged. The cycle is then repeated. To minimize this fluctuation in candle-power and heating value, a tank containing a considerable supply of gasoline is sometimes connected to the carbureter with a ball and float valve, by which the height of the gasoline in the carbureter is replenished as fast as evaporated. It is claimed that this is an unnecessary refinement when a separate mixer is employed.

When air is brought so intimately in contact with highly volatile gasoline the quantity of gasoline vapor that passes off with the air may be considerably in excess of that required to saturate the air at the final temperature. The gas from the carbureter is, therefore, not then in condition to use; it is too rich and unstable as to condensibility. As has been shown, and perhaps explained, Redwood is authority for the apparently contradictory statement that while air will require only 22 per cent of gasoline vapor to saturate at 60° F., yet when the air is bubbled slowly through a series of six tubes containing gasoline of the same gravity at the same temperature, the mixture of vapor and air passing off consisted of more than 50 per cent vapor.

The carburetted air from the carbureter is passed into the mixer (Fig. 10), The mixer consists of a small holder rising and falling above the water in an enclosing metal cylinder. The holder has trips which open and close cocks at its lowest and highest points, thereby operating automatically by the flow of the gas. There is a test light and an adjusting cock for regulating the proportion of air to be mixed with the highly carburetted air from the carbureter, and a valve which is designed to control within certain limits the proportions of air from the blower and carburetted air from the carbureter.

This is known generally as the cold-air process; under proper and reasonable supervision it affords a safe and practical means of illumination and heating. When installed so as to comply with the underwriters' requirements it involves no increase in insurance rates. While designed and intended only for a mixture above the explosive limits it could be mechanically adapted to yield a mixture below the explosive limits.

3. To convert gasoline into a vapor by the application of external heat and then by suitable mechanical means to mix the gas or vapor so formed with any desired proportion of air. This process has been applied in a number of types of air-gas machines. Generally, the heating device is in the form of a coil through which the gasoline passes and which is heated by a burner.

Machines of this class are simpler as to number and complexity of parts, but the direct application of flames to a coil containing gasoline has not been considered safe by most insurance companies, and their use is therefore restricted.

4. The fourth method consists of inducing a current of air into a small tube by a jet of steam and at the same time allowing sufficient gasoline or naphtha to enter to condense the steam and combine with the air. The latent heat of the steam in this process is intended to compensate for the refrigerating action of the gasoline or naphtha in passing to the state of vapor.

With both the third and fourth methods petroleum naphtha of a considerably lower gravity may be used, say 72° to 68° B. (sp. gr., .6931 to .7071); while with the cold-air process gasoline not heavier than 82° B. (sp. gr., .6604) can be used without the necessity of pumping the residue from the carbureter oftener than once in 6 months.

The fourth method, one of the earlier inventions of Hiram Maxim, is probably best for a large output of gas. Fig. 12 shows one of these machines with a sectional view of the steam injector for air and naphtha. Steam at about 60 pounds gauge pressure, controlled by a regulator, is supplied to chamber "A," from which it issues at high velocity through injector nozzle "L" into tube "G," drawing in air from "C" by the injector action. At the other end of tube "G" a secondary injector action takes place, naphtha entering by the adjustable valve "D." The latent heat of the steam vaporizes the naphtha and by doing so the steam itself becomes condensed. The naphtha vapor and air unite and pass into the gas holder, while the condensed steam is trapped away. The operation of this machine is entirely automatic. When working close to its capacity very little of the gas remains in the holder, but when the consumption of gas is reduced to a minimum the holder fills with gas, and by means of a system of trips and levers the process is interrupted by the closing of the steam nozzle; when the holder descends the operation is reversed, the steam

nozzle is opened and the making of gas continues as before. By regulating the adjustable air and naphtha valves any desired mixture of vapor and air can be obtained, and in larger quantities than with any of the cold-air processes.

The simplicity of carburetted-air processes is evident; no purifying of the delivered gas is required, and all the heat of the liquid fuel is directly transferred to the air and vapor mixture.

The burners used for securing illumination through the agency

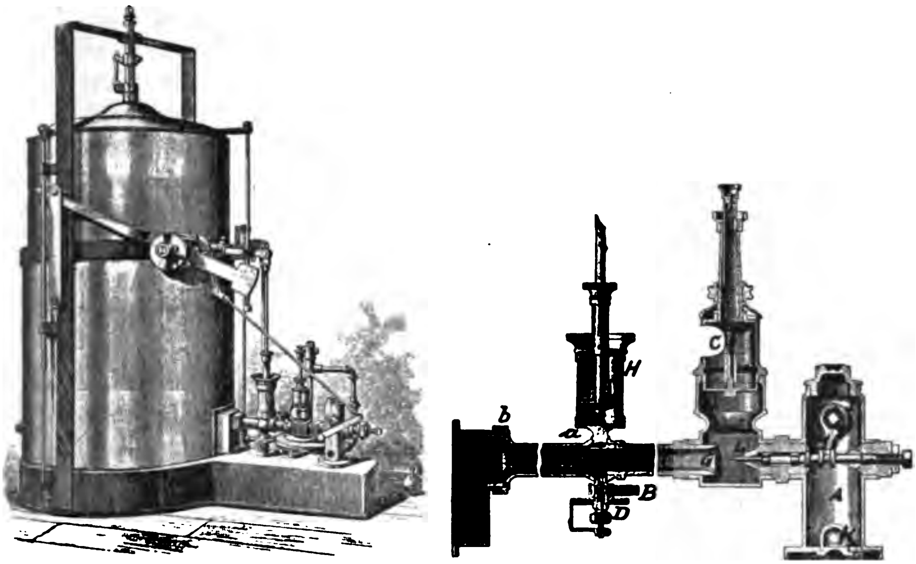

Fig. 12.

of carburetted air are the ordinary flat-flame lava tip, and the various forms, both upright and inverted, of mantle burners.

Where no mixer is installed and the gas is consumed directly from the carbureter the lava-tip burner has a small set-screw, by which the gas can be adjusted in its flow so as to prevent heavy and smoky flames.

The specific gravity of the gas being much greater than that of coal or water gas, it requires a larger opening in the check for the same quantity of gas to flow through, and in some cases larger openings for the air through the Bunsen are required.

When a well-designed mixer is installed with the machine, as it

always should be, there is no inconvenient fluctuation in the candle-power of the light from the mantle burner.

When burning a mixture containing less than 2 per cent gasoline—below the range of explosibility—the Bunsen burner on the Welsbach burner is omitted entirely, as the gas contains sufficient air for a non-luminous flame.

The extent to which carburetted-air gas is used for lighting cannot be determined accurately from available statistics. It occupies a field similar to acetylene—that of isolated plants and plants for the general supply of small towns and villages. From many of the plants, especially those operated by municipalities, no answers are received to applications for information; in many other cases the answers are vague and ambiguous. Brown's Gas Directory shows that in the United States there are 124 town plants. It is claimed that, including the smaller plants, there are twice this number. A fair estimate of the amount of gas made and distributed by the 124 town plants is not less than 166,000,000 cubic feet a year. The gas is used for street lighting as well as for domestic consumption. In some cases the gas is distributed through a considerable mileage of mains. The prices charged vary from $1.25 to $2.50 per 1000 feet. One of the largest companies reports a total annual sale of 35,000,000 cubic feet sold through 126 meters and 44 public lamps and distributed through 8½ miles of mains.

All things considered, perhaps the field in which carburetted-air gas can demonstrate its greatest economic efficiency is in that of factories using various special heating devices of comparatively small individual capacity. The plant being installed primarily for this special heating, it can also be employed economically for lighting.

Acetylene

Acetylene is one of the group of hydrocarbons covered by the general formula $C_{2n}H_{2n}$, its own formula being C_2H_2; that is, its one molecule contains two atoms each of carbon and hydrogen. This gas has long been known to the chemists; and even as produced synthetically, by uniting the elements in the compound, the record goes back to 1836, though the reaction was not then fully understood. In 1862 Woehler announced the discovery of the

production of acetylene from calcium carbide made by heating to a very high temperature a mixture of charcoal with an alloy of zinc and calcium. Acetylene was known by chemists, and gas engineers also, as one of the heavy illuminants analytically produced in small percentages during the destructive distillation of coal in the making of coal gas and in the generation of water gas, and its high value as an enricher was understood.

Acetylene polymerizes at about 600° C. (1112° F.), that is, at elevated temperatures it is converted into other hydrocarbons having the same percentage composition, but containing more atoms of carbon and hydrogen in their molecules. Acetylene readily polymerizes to benzene, C_6H_6. This change is indicated by the equation $3C_2H_2 = C_6H_6$. Benzene, like acetylene, contains by weight almost exactly 92.3 per cent carbon and 7.7 per cent hydrogen, but its molecule contains six atoms of each element instead of 2, as in the case of acetylene. It will be seen later that this instability of acetylene, together with its other characteristics, has a most important bearing upon its treatment and application and the precautions to be taken against accidents.

In 1892 Thomas M. Willson, an electrical engineer, while experimenting on the production of metallic calcium, employing therefor an electric furnace of high voltage in which was a mixture of lime and coal-tar, obtained a mass which he accidentally discovered contained calcium carbide, and which gave off acetylene when immersed in water. Willson was the first to demonstrate that acetylene could be obtained from calcium carbide in sufficient quantities and at a cost that would secure it a place in the industrial arts.

This discovery of Willson's undoubtedly increased and intensified the interest in electro-chemical research and in synthetic chemistry, which two fields of research hold out much of promise for the benefit of mankind. It has also served to strengthen the theory or surmise that metallic carbides exist in the earth's interior, and are the origin of petroleum and natural gas. Calcium carbide is composed of one part of calcium and two parts of carbon, as shown by the formula CaC_2. It is a hard, crystalline substance, dark gray in color, specific gravity about 2.22. One cubic foot of compact carbide therefore weighs about 138 pounds.

The two highly refractory substances, lime and carbon, are forced to combine under the action of excessively high tempera-

tures, as most readily obtained in the electric furnace. The reaction is shown by the equation

$$\underset{\text{(Quicklime)}}{CaO} + \underset{\text{(Carbon)}}{3C} = \underset{\text{(Calcium Carbide)}}{CaC_2} + \underset{\text{(Carbon Monoxide)}}{CO}$$

which shows that 56 pounds of lime combine with 36 pounds of carbon to form 64 pounds of calcium carbide and 28 pounds of carbon monoxide. Roughly, then, for the making of a long ton of the carbide, there is required a short ton (2000 pounds) of lime and 1275 pounds of carbon.

In the manufacture of the carbide the purity of the raw material is of prime importance. Those forms of carboniferous material in which there is a low percentage of fixed carbon are to be avoided as the rapid evolution of gaseous products therefrom is likely to lead to explosions.

The calcium carbonates, such as limestone, marble, etc., from which the lime or calcium oxide is prepared, must be low in content of magnesia, alumina, silica, sulphur and phosphorus. The ordinary limekiln cannot be used because of the impurities that would be introduced therefrom. As it takes about 100 pounds of carbonate of lime to yield 56 pounds of the oxide, those impurities not driven off with the carbonic acid would be nearly doubled. These necessary precautions led to the general practice of calcining the carbonate at the carbide factory.

After mixing the lime and carbon in proper proportions they are fused by a powerful electric current. Resistance and arc furnaces are both used. The furnace must be operated under uniform heating. For the generation of the heavy currents required recourse may now be had to more or less remote water powers if otherwise desirable, as railroad transportation of the carbide is no longer hampered by onerous restrictions. The carbide is necessarily packed in tightly sealed cans to protect from moisture.

While a generation has not yet elapsed since the first introduction of acetylene to the commercial world the files of the patent offices contain such a multiplicity of applications, granted and rejected, that it would be futile at this time to touch on this branch of the subject. Many of these applications show that the inventors neither understood the principles involved nor the progress of the art, an ignorance frequently accompanying much so-called invention.

The production of carbide in Europe in 1908 is approximated as follows:

	Tons
Sweden and Norway	35,000
France	26,000
Switzerland	30,000
Italy	31,000
Austria	20,000
Germany	40,000
Scattered	10,000
Total	192,000

Practically all of this carbide was used for the production of acetylene.

Coming now to the manufacture of acetylene, it is to be regretted that more complete and accurate data cannot be had as to its use as an illuminant, and especially in the United States. Brown's Directory of Gas Companies records 184 acetylene town plants in operation the first of this year. These works report a total output of 18,500,000 cubic feet. A paper read before the Illuminating Engineering Society in 1909 is authority for the statement that there were at that time 290 towns lighted with acetylene. It can be understood readily that the record in Brown's Directory, depending for its facts as it does upon answers to question sheets, may be quite incomplete by reason of the indifference of those in control, and especially so in case of the municipal plants.

In addition to the acetylene so distributed, the total is considerably increased by that used in private houses, contractors' plants, car lighting and portable lamps, particularly automobile search-lights.

The rate charged for acetylene by the town companies seems to run from 1½ to 2 cents per cubic foot, or $15 to $20 per 1000 cubic feet. Under efficient management, as to installation and operation, these rates are said to afford a fair return on the investment.

To comprehend the precautions to be taken in the use of calcium carbide and acetylene, there must be borne in mind the difference between exothermic and endothermic reactions.

Exothermic compounds are those whose formation from elementary substances is attended with *liberation* of heat, and whose decomposition into simpler compounds or elementary substances is attended with *absorption* of heat.

Endothermic compounds are those whose formation from elementary substances is attended with *absorption* of heat, and whose decomposition into other compounds or elementary substances is attended with *liberation* of heat.

These latter compounds are not very numerous, they are more or less unstable, and some of them are resolved into their elements with explosive force.

Acetylene is an endothermic compound.

Acetylene is obtained from calcium carbide through a double decomposition. The first step is shown by the equation

$$\underset{\text{(Calcium carbide)}}{CaC_2} + \underset{\text{(Water)}}{H_2O}$$

$$= \underset{\text{(Acetylene)}}{C_2H_2} + \underset{\text{(Calcium oxide or lime)}}{CaO}. \qquad (1)$$

But the quicklime, CaO, in the presence of *an excess* of water, will be found in the form of slaked lime, or calcium hydroxide, $Ca(OH)_2$, as shown by the equation

$$CaO + H_2O = Ca(OH)_2. \qquad (2)$$

As these reactions in the presence of sufficient water may occur simultaneously, the double reaction can be shown by the equation

$$CaC_2 + 2H_2O = C_2H_2 + Ca(OH)_2. \qquad (3)$$

This is an exothermic *reaction* because the quantity of heat *liberated* exceeds the quantity of heat absorbed. There is some little question as to the heat of *formation* of calcium carbide, authorities varying from -0.65 calories (large) to $+3.9$. But these differences of opinion do not affect the question as to whether the reaction as a whole results in absorption or liberation of heat; it only affects in minor degree the quantity of heat liberated.

The heat of formation of $Ca(OH)_2$ (exothermic substance) is $+160.1$ large calories; the heat of formation of water (exothermic substance) is $+69$, and hence for decomposition is -69; taking heat of formation of calcium carbide as $+3.9$, for decomposition it is -3.9. The heat of formation of acetylene is -58.1. As the formation of $Ca(OH)_2$ is obtained by the *decomposition* of the water and the carbide and the *formation* of the acetylene, we have heat liberated in the formation of the $Ca(OH)_2$ 160.1, and the heat *absorbed* as follows:

Formation of acetylene	− 58.1	Endothermic substance.
Decomposition of water	− 69.	Exothermic.
Decomposition of carbide	− 3.9	Exothermic.
Total	−131.0.	

Deducting the 131 absorbed, from the 160.1 set free, we have as a net result 29.1 large calories liberated.

While this *reaction* as a whole is exothermic, acetylene as a *substance* is seen to be decidedly endothermic, and so is ready to liberate large quantities of heat whenever the conditions for decomposition obtain.

While this reaction may be modified it should be pointed out that the reaction where there is no excess of water, as indicated in equation (1), produces in practice results which are quite different from those obtained where there is excess of water, as indicated in equation (3).

In the acetylene generators of the most modern and usual pattern, some of the surplus water is evaporated by the heat liberated, and some of this water vapor, even at low temperatures, is carried away with the escaping gas. If the heat liberated during the decomposition of the carbide is not otherwise absorbed, it is sufficient in amount to vaporize almost exactly three parts by weight of water for every four parts of carbide attacked. But if this quantity of heat were expended upon some substance, such as acetylene or calcium carbide, which, unlike water, cannot absorb an extra amount by changing its physical state, as from liquid to gas, the heat thus generated during the decomposition of the carbide would be in evidence to a far greater extent. For reasons that can be indicated only within the time allowed me, it is essential for good working that the temperature of both the acetylene and the carbide shall be prevented from rising to any considerable extent.

Experiments were conducted by Caro and by Lewes to determine the temperature of the carbide due to decomposition. Caro's experiments showed a maximum temperature of 280° C. (536° F.). Lewes' experiments gave a maximum temperature of 807° C. (1480° F.). The temperature attained is in part dependent upon the time elapsed in the reaction, for the longer the time the greater the opportunity for the escape of heat liberated. The divergence in the results obtained by Caro and Lewes is explained by the difference in the design of the generators and the speed at which they were operated. In Lewes' generator little or no provision was

made against overheating, and it is not to be supposed that such temperatures as were observed by Lewes are found in a commercial generator. But his determination is important as showing the danger to be avoided, for the temperature he found is considerably above that at which acetylene decomposes into its elements in the absence of air, namely, 780° C. or 1436° F. Excessively high temperatures in the generator must be avoided, because whenever the temperature in the immediate neighborhood of a mass of calcium carbide which is evolving acetylene under the attack of water rises materially above the boiling point of water, one or more of three objectionable effects is produced; namely, upon the gas generated, upon the carbide decomposed, or upon the general chemical reaction then taking place. Time does not permit a full discussion of the questions here involved, but a few hints may be given.

Lewes points out that not only does acetylene decompose at 780° C., but it begins to polymerize at 600° C. (1112° F.). Suppose acetylene polymerizes into benzene, the burner adapted to the efficient utilization of the former will not be so adapted for benzene. Furthermore, under certain conditions, the benzene liquefies and deposits with water vapor in the pipes. An additional trouble from polymerization occurs when the temperature rises above the point at which benzene is formed, for then other hydrocarbons may be formed having a higher proportion of carbon than is present in acetylene and benzene, setting free non-luminous hydrogen, and thus reducing the illuminating value of the gaseous mixture. In certain experiments by Lewes the loss in candle-power was found to be a reduction from 240 to 126. Another effect of heat upon acetylene has already been indicated. Being an endothermic substance it gives out heat upon decomposing. It decomposes at 780° C. when free from air, a spark, or shock, or pressure of 30 pounds or more being sufficient to effect the change. This change raises the temperature and so increases the pressure of the disassociated hydrogen, and may cause the containing vessel to explode. If air is present, as it may be through bad design of apparatus or incompetent attendance, the acetylene can be ignited at 480° C. (896° F.). Under certain conditions 25 per cent of air and 75 per cent of acetylene are explosive.

The extreme limits of explosibility of acetylene mixed with air are variously stated. Clowes gives the extremely wide range of explosibility from 3 per cent to 82 per cent of acetylene. Le

Chatelier gives 2.9 per cent to 64 per cent. Eitner made exhaustive tests with several gases, in each case the mixture being *saturated with aqueous vapor,* thus *reducing the limits of explosibility.* For acetylene he gives from 3.35 to 52.30 per cent. Teclu, experimenting with a *dry mixture,* determined the limits as 1.53 to 59 per cent. These results naturally are changed if the mixture contains other gases besides acetylene and air, but enough has been said to show that acetylene cannot be handled carelessly. This is emphasized by Eitner's experiments, comparable but not giving extreme limits, which gave as the limits for coal gas 7.90 to 19.10 per cent, or a range of only 11.20 per cent against acetylene range of 48.95 per cent, as shown above.

In the generator the effect of heat on the carbide itself may be troublesome. If part of the gas polymerizes part may so be resolved into tar, which coats the carbide still unattacked and so protects it more or less from further attack, thus reducing the output and leaving the residue with a content of acetylene, which may later occasion trouble during or after removal.

The effect of accumulating heat in the generator itself has to be guarded against. For example, at a temperature as low as 200° C. (392° F.), if the ordinary solder were used in the joints it would be melted and the vessel become unsafe. This serves to point to the fact that the materials used and the minor details of construction in a generator may be such as to condemn a design generally commendable.

Having indicated most superficially some of the conditions to be considered in the design and construction of acetylene generators, with the aid of diagrams taken from Leeds and Butterfield's work entitled "Acetylene, Its Generation and Use," I shall show in a general way how these conditions are met, but without attempting to discuss the relative advantages and disadvantages of the several types.

Acetylene generators may be roughly classified as follows:

1st. Carbide to water.
- (a) Non-automatic.
- (b) Automatic.

2d. Water to carbide.
- (a) Non-automatic.
- (b) Automatic.

In general, the type having the widest limits of safety is that in which a small quantity of carbide is introduced into a considerable body of water, the acetylene as it bubbles through the water passing directly out and into a holder. If this holder has ample capacity for the maximum night's demand, it can be filled with gas during the day and the generator locked for the night. This non-automatic form may be criticized on the ground of first cost.

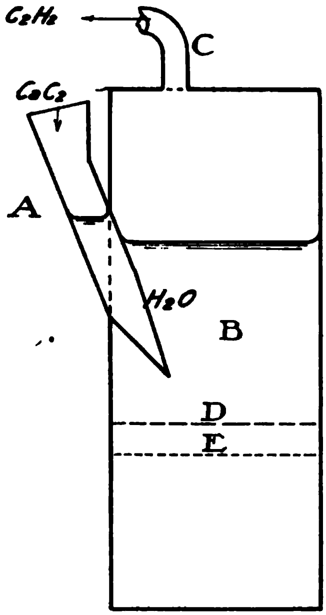

FIG. 13.

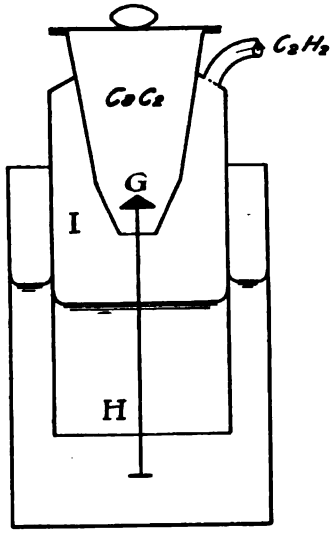

FIG. 14.

FIG. 13.—Acetylene Generator. Non-Automatic. Carbide to Water Type.
FIG. 14.—Acetylene Generator. Automatic. Carbide to Water Type.

If the introduction of carbide is controlled by an automatic device which admits carbide automatically as the acetylene is consumed, a smaller generator and holder can be employed.

Figs. 13, 14 and 15 show types of carbide to water generators.

Fig. 13 represents the non-automatic type. The carbide is fed by hand through the chute A into the generator B. The generator is filled with water above the opening of the chute to prevent the gas from escaping through the chute. Grids D and E catch and support the lumps of carbide, permitting the acetylene to be com-

pletely liberated before permitting the mass to mix with the sludge of slaked lime in the bottom of the tank. The carbide cannot be used in small lumps, as then the generation of acetylene would be sufficiently active to blow the seal and allow the gas to escape through the chute.

Fig. 14 shows an automatic generator of the first class. The carbide is held in a hopper which is supported by holder bell I, which rises and falls according to the volume of acetylene contained. The hopper is closed at the bottom by a valve G, from

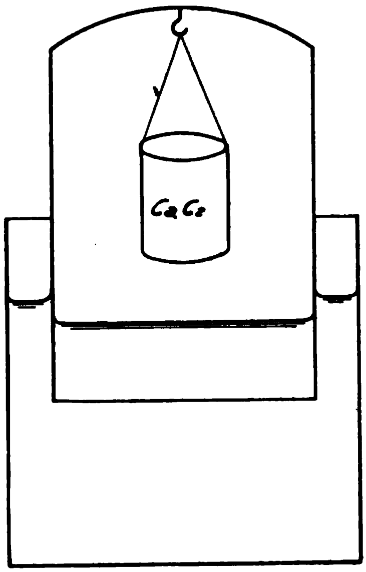

FIG. 15.

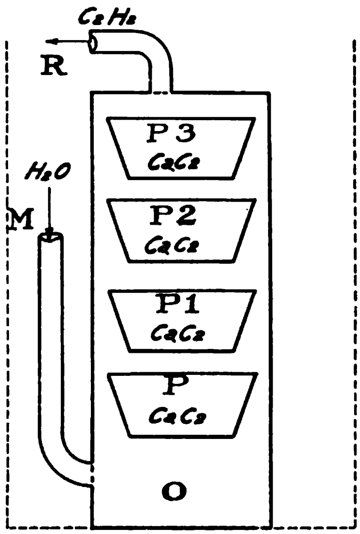

FIG. 16.

FIG. 15.—Acetylene Generator. Automatic Dipping. Carbide to Water Type.

FIG. 16.—Acetylene Generator. Water to Carbide Type. Water Inlet at Top.

which depends a rod H. As acetylene is withdrawn from the bell the bell falls until the rod strikes the bottom of the tank, the valve is thus forced open permitting more carbide to fall into the water, more acetylene is released, the bell again rises until the valve seat and valve engage, when the supply of carbide is again stopped.

Fig. 15 shows a dipping generator. The carbide is held in a perforated vessel which hangs from the inside of the crown of the

holder bell. As the acetylene is consumed the bell falls until the carbide dips in the water, when acetylene is again liberated.

Figs. 16, 17 and 18 show types of water to carbide generators. Fig. 16 shows a generator in which the carbide is contained in a series of pans, P, P1, P2 and P3, a small quantity in each pan. Water is admitted at the bottom through pipe M. As each pan is flooded the acetylene rises to the top of the tank and passes out

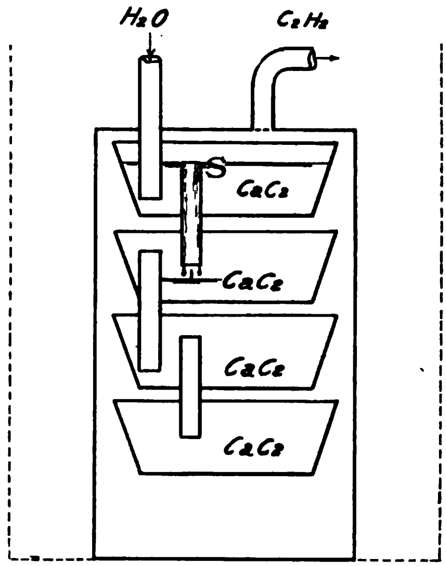

Fig. 17.—Acetylene Generator. Water to Carbide Type. Water Inlet at Top.

at R. The gas passing out is charged with water vapor, and this water acting upon the carbide in the upper pans produces "after generation," which is an objectionable feature.

Fig. 17 shows a better type. The carbide is contained in pans as in the previous case. Here the water is admitted at the top of the tank and first acts on the carbide in the top pan. The gas passes off without coming in contact with the carbide in the other pans. As the first pan is flooded the water overflows through the pipe S to the second pan. This is repeated until the carbide in the last pan is attacked. The acetylene escapes from the pipe at the top of the tank, as shown.

Fig. 18 shows a generator not to be commended. The carbide is contained in the tank T. Water enters at the top in drops or a fine stream. This type produces "after generation" and dangerous overheating.

Generally speaking, in the water to carbide generators the generator is opened to the air while being charged with fresh carbide; this is a decided disadvantage, for, as already shown, acetylene should be guarded from mixing with air on account of its wide range of explosibility.

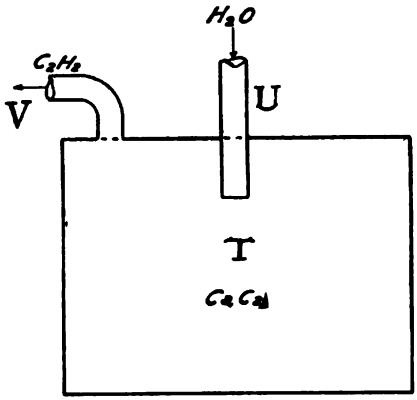

FIG. 18.—Acetylene Generator. Water to Carbide Type. Crude Form.

What I have said fails to show the great variety of apparatus actually employed or the manner in which the several types merge into each other. I have not attempted to show the complete acetylene installation, including the parts for generation and governing. It should be pointed out that it is necessary either to use a pure carbide or provide means for purifying the acetylene, as otherwise compounds of phosphorus, silicon, ammonia and sulphur might be present rendering the gas objectionable on the score of spontaneous inflammability or non-hygienic qualities. Leeds and Butterfield's work give the rules and regulations adopted by governments and insurance companies for the construction and installation of acetylene plants.

The carbide is sold in several sizes. For generators the size varies from 3½ inches by 2 inches down to ¼ inch by 1/12 inch. For lamps, from 1 inch by ½ inch down to dust. The rate of

evolution is inversely proportional to the size of the lump. Lumps coated with dust may give irregularity in operation.

Acetylene liquefies at 0° C. and about 21½ atmospheres pressure. It is then most unstable, spontaneous disassociation with explosive force being due to occur on the application of a spark or when shocked. After quite a number of disastrous accidents it is now generally understood that liquid acetylene is too dangerous to use. As before mentioned, the gas is liable to explode if heated to 780° C. or if held under a pressure of 2 atmospheres absolute, or above.

Acetylene is readily soluble in many liquids, and this property is utilized to bring the acetylene into small compass. Acetone, at ordinary temperature and atmospheric pressure, will dissolve about 25 volumes of acetylene, and at 12 atmospheres will dissolve about 300 volumes. Acetone is an exothermic substance with a composition shown by the formula C_3H_6O, and hence combustible, and within certain limits of pressure its presence tends to decrease the severity of explosion. At 20 atmospheres pressure the acetone adds to the danger from explosion. Acetylene dissolved in acetone carried up to a pressure of 10 atmospheres is safely employed, but there are practical objections to its use in this liquid form. To overcome these objections the cylinders are filled with some porous material which does not react on the acetone. A material is used which has a porosity of 80 per cent, that is, when the vessel is apparently full of the material about 20 per cent only of the space is really occupied. The portable cylinders for this service cannot be filled with acetone, for the reason that ample space must be left for expansion as the liquid takes up the gas. A cylinder having a normal capacity of 100 volumes will have say 20 volumes taken up by the porous filling, and can safely be charged with 40 volumes of acetone. This 40 volumes of acetone dissolves $40 \times 25 = 1000$ volumes of acetylene; and by compression to 10 atmospheres this is increased to 10,000 volumes. In this form acetylene is sold under various trade names and used for automobile head lights and similar service where limited storage capacity is of decided moment.

Acetylene, under favoring conditions including moisture, will combine with copper to form acetylide of copper, an explosive compound. As acetylene is now generally produced and used these conditions are not apt to obtain, so the danger from this source is

now not regarded seriously. Copper alloys and compounds should not be employed in the construction of parts of plant exposed to the gas or in the process.

Straight acetylene, burned in an open-flame burner of a character and size best adapted to give the highest illuminating value, the burner being so placed as to carry to the photometer disc the strongest horizontal rays, the bar readings being calculated pro rata to a consumption of 5 feet an hour, gives a candle-power of from 240 to 250.

The general practice of selecting the burner and rate of consumption so as to develop best efficiency of the gas instead of being confined to one type of burner and a rated consumption of 5 feet an hour, has received the approval of the Gas Referees of London acting under Parliamentary powers.

The specific gravity of acetylene is .9056, usually taken as .91.

For self-luminous flames, lava-tip burners are employed, the gas issuing either from a slot or two holes, both producing flat flames. With the latter form the flat flame is produced by the impinging of the two currents of gas against each other, the plane of the flame being produced at right angle to the plane of the two holes. The burners are made in many different forms in the effort to overcome difficulties due to the richness of the gas and its instability. The richness of the gas made it necessary to employ small burners or to make extra provision for injecting air into the body of the flame by the action of the issuing gas. This was best accomplished by some form of two-jet burner, which dragged in the air at a point between the jets and below the flame. To better accomplish this result burners were devised with two tips so as to separate farther the two jets of gas. Further, to assist in the injection of air, acetylene is burned at a pressure far in excess of that employed with coal gas. Its high specific gravity also calls for additional pressure. The design of acetylene burners well illustrates that burners must be designed to supply such a quantity of air to the flame as will produce a maximum incandescence. If one of these burners were used with coal gas, so much air would be dragged in that the carbon particles of this thinner gas would be consumed with little or no preliminary incandescence.

The comparatively high efficiency of the acetylene flame is due not alone to the high carbon content; an important factor is the high flame temperature, which is in part the result of liberation

of heat at time of disassociation of this endothermic gas. Mahler gives the flame temperature at 0° C. and 760 mm. as 2350° C. or 4642° F. Le Chatelier gives 2100° C. to 2400° C.

Acetylene is also employed with incandescent mantles, resulting in a considerable increase in candle-power, this gain according to different authorities being from 160 to 200 per cent. For certain special applications a still larger gain has been secured. There are decided difficulties to be overcome and advantages to be abandoned in using acetylene for incandescent lighting, and the high efficiency and the whiteness of the self-luminous flame make it less necessary or desirable to overcome these difficulties.

Acetylene is also employed for illumination in the form of carburetted acetylene or carburylene, and in this form it is more advantageously applied to incandescent lighting, but time does not permit a discussion of this branch of the subject.

In connection with illuminating engineering, the color of the acetylene flame is of great importance. A comparison with sunlight and other light sources will be given in another of these lectures.

Acetylene can also be used for heating. Its calorific value per foot is 363 large calories, or 1440 B. t. u., which is about two and one-half times that of city gas. The comparison is not favorable to acetylene, however, when relative costs are considered.

Within the limits of a single lecture, inordinately long, it is true, I have, according to instructions, endeavored to cover three sources of illumination. Many lectures could be devoted advantageously to each of these. Acetylene alone could not be covered completely in many lectures.

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AUER VON WELSBACH

V (2)

INCANDESCENT GAS MANTLES

By M. C. Whitaker

CONTENTS

Introduction

Heat sources: chemical, electrical.
Combustion.
  Substance: gas, wood, coal, etc.
  Supporter of combustion: oxygen, air.
  Kindling temperature: electric spark, lighted match, etc.
Chemistry of combustion.
  Marsh gas + oxygen = water vapor + carbon.
  Carbon + oxygen = carbon dioxide.
Open tip combustion.
Bunsen burner combustion.

Incandescent Gas Illumination

Principles involved.
History: Hare, Drummond and Claymond lights, Siemens-Lungren lamp, Auer von Welsbach lamp.
Bunsen burner: history, construction and chemistry of operation.
Adaptations for use with incandescent mantles.
  Upright and inverted.
  Single, cluster and arc.
  Inside and outside.
Upright burner construction.
  Bunsen tube.
  Check for gas; plate, needle, multiple hole, check; air adjustment; gauzes; gallery.
Inverted burner construction.
  Types: vertical, horizontal and goose-neck burners; velocity, gravity and buoyant action in downward flow of mixture.
  Checks for gas; air adjustment; means for overcoming flash-backs; crown for glassware.

Gas Mantles

Process of manufacture: history, knitting, washing, saturating, incinerating, shaping, collodionizing, trimming and inspecting, packing and shipping.
Physical structures of mantles.
  Basic fibers: cotton, ramie, artificial silk.
  Threads, weaves, stitches, etc.

Chemicals and sources.
 Lighting principles; thorium and cerium.
 Thorium; source (monazite, thorianite); manufacture, market, use.
 Collodion; composition, manufacture, use.

Types of mantles: upright and inverted, railroad train, sizes, pressure, rag, acetylene, kerosene, etc.

Quality and service characteristics as determined by process of manufacture.
 Cotton: shrinkage, depreciation in candle-power; color value; physical strength.
 Ramie: ditto, etc.
 Artificial silk: ditto, etc.

Introduction

Assuming that the illuminating power of a gas flame is derived from the heating of solid particles to incandescence, the practice of gas illumination divides itself into two general principles:

First. Where the solid incandescent material is supplied by the decomposition of the gas in the process of combustion. (Open-tip flame.)

Second. Where the gas is completely consumed in a Bunsen burner for the production of the maximum amount of heat and a permanent incandescent material is supplied as a part of the apparatus. (Incandescent gas system.)

The first steps toward the improvement of the efficiency of gas for lighting was made on the first of these principles by preheating the gas before it reached the point of combustion in the so-called regenerative burner of the Siemens-Lungren or Gordon-Mitchell type (Fig. 1). There are some of these regenerative lamps in use at the present time. The regenerative burner was the most effective ever produced by following the first principle mentioned above, and gave the most efficient results up to the introduction of the incandescent mantle system, which is based on the second principle.

Professor Robert Hare (Philadelphia Chemical Society, 1802) first fully described a form of "incandescent" gas light, which is the basic principle now utilized in this industry.

At a meeting of the Philadelphia Chemical Society, held in December, 1801, he showed experiments and described this incandescent lime light as follows:

"The cock of the pipe communicating with the hydrogen gas was then turned until as much was emitted from the orifice of the cylinder as when lighted formed a flame smaller in size than that of a candle.

Under this flame was placed the body to be acted on, supported either by charcoal, or by some more solid, and incombustible substance. The cock retaining the oxygen gas was then turned until the light and heat appeared to have attained the greatest intensity. When this took place, the eyes could scarcely sustain the one, nor could the most refractory substances resist the other."

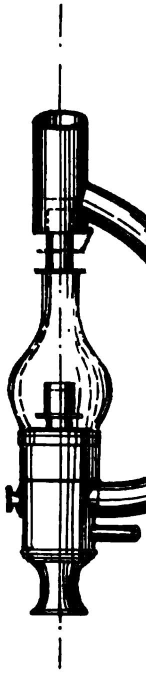


FIG. 1.—Regenerative Lamp.

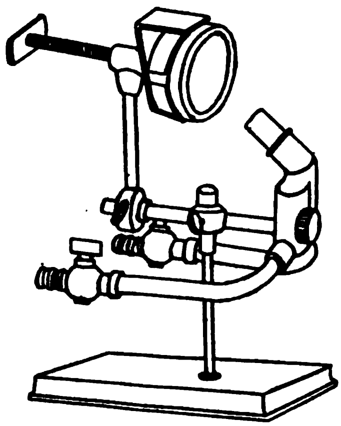


FIG. 2.—Drummond Calcium Light.

Henry Drummond, in 1826, made use of the incandescent lime light, similar to that suggested by Professor Hare, for signaling. Drummond's application of this principle of producing an illumination of high intensity was adopted generally, and he is usually credited with the invention. The lime light is sometimes called the "Drummond light" (Fig. 2).

At the Crystal Palace Exposition in Paris in 1883 a lamp of the inverted type was shown in which the illumination was produced by a platinum basket suspended in a blast flame. The life of the basket was limited to 50 or 60 hours.

Various other lamps for the application of the principle of supplying the incandescing material were suggested, such as cones

made from platinum wires covered with a refractory coating, perforated baskets, grids placed above the flame of the fish-tail burner, etc.

The greatest step in the development of a commercial incandescent gas light was made by Dr. Carl Auer von Welsbach. In 1886, Dr. Auer, while a student in the laboratory of Professor Robert Bunsen, in Heidelberg, discovered that the ash formed by saturating a cotton fabric in a solution of erbium salts and burning out the organic matter would take the shape of the original fibers, and would adhere to form a mesh of considerable strength. This finely divided ash fabric, when suspended in the flame of a Bunsen burner, became intensely luminous. Erbium, however, produces green light. Nevertheless, the principle of forming an attenuated but closely adhering ash was established by Dr. Auer in these experiments, and he immediately proceeded to develop this idea with a view to producing a commercially desirable light by heating oxide webs which he called "stockings" or mantles.

His early mantles were made from a mixture of lanthanum and zirconium oxides. The light given by this mixture was not satisfactory, and the investigation was continued until he discovered the wonderful luminescence obtained with a mantle made from the rare oxides of thorium and cerium.

Incandescent Burners

The earlier burners constructed to use Auer's invention were designed for use with the lanthanum-zirconium mantle, which did not give the high candle-power given by the present mantle. These burners were consequently very large and clumsy and bore a very remote resemblance to the modern types.

Modern Types

The present practice in incandescent burner construction should be divided, for clear discussion, into—

First. Individual upright burners.

Second. Individual inverted burners.

Third. Gas arc lamps (upright burners).

Fourth. Gas arc lamps (inverted burners).

Fifth. Lamps for special application (pressure oil lamps, railway coach lamps, kerosene lamps, etc.).

Upright Burners

The functional parts of the upright incandescent burner may be divided into (Fig. 3):

(a) Bunsen tube.
(b) Bunsen base.
(c) Gas-adjustment means.
(d) Air-adjustment means.
(e) Mixing chamber.
(f) Gallery to support chimneys, glassware, reflectors, etc.

FIG. 3.—Upright Burner Cut to Show Interior Construction.

The Bunsen tube is carefully designed to meet a wide range of gas conditions, such as fluctuations in pressure, gravity, etc., and still produce a mixture which has entrained the proper quantity of air to produce complete combustion at the gauze line. The dimensions of this tube have been carefully determined in experience, and are comparatively uniform in all styles of standard burners.

The Bunsen base is usually turned from solid brass bar and threaded internally to fit the average run of ⅛-inch gas nipples

rather than any standard thread. This base is also adapted to carry the gas-adjusting device and to form an assembly base for the entire lamp.

A gas adjustment is an essential feature of the standard burner used in this country. Some foreign burners, and many of the early burners in this country, had a fixed gas orifice, but the variation in density and pressure of the gas in different localities have compelled the modern gas burner to include some means for adjusting the gas flow.

There are several prevailing types of gas checks, some of which fulfil the function of regulating the flow of gas, but fall far short of meeting other essential requirements.

The efficiency of burners of this type is largely dependent upon the *velocity of the gas jet,* and its consequent ability to entrain the amount of air necessary to produce complete combustion. Any construction which tends to cut down this jet velocity seriously affects the efficiency and proper operation of the burner unless the initial gas pressure is high enough to produce a proper jet velocity in spite of the design of the check. Low and variable pressures are common conditions and, as a consequence, must be provided for in all designs intended for general sale and use.

A single round hole through a thin plate offers the minimum amount of resistance to the flow of the gas stream and, as a consequence, gives the maximum jet velocity in the Bunsen tube. An iris diaphragm, similar to the device used in a camera, has been suggested as the ideal way to construct an adjustable single-hole check, but the cost of construction and the mechanical difficulties involved in making it gas-tight prevent its general adoption.

Among the adjustable checks in general use the preferred types seem to be included in the following general designs:

First. The Mason check, which is a series of round holes in superimposed plates, one of which may be rotated upon the other in such a way as to bring more or fewer holes into action, depending upon the direction of rotation. While the number of small holes offers somewhat more friction to the flow of the gas than the ideal single hole, it is thought that this device, which is capable of economical and reliable mechanical construction gives the most efficient results over the widest range of conditions.

Second. The *annular-orifice* check is produced by inserting a needle in a single round hole and providing a mechanical construc-

tion which permits the needle to be drawn in or out in relation to a stationary hole, or a stationary needle with a cap-orifice arranged to be raised and lowered. Obviously, the annular orifice, which may give satisfactory results with favorable conditions, will offer unfavorable resistance to the flow of the gas on lower pressures and thereby affect the mixture.

FIG. 4.—Upright Burner.

Adjustment of the air supply is usually automatically taken care of by the regulation of the gas flow when the composition and other conditions are normal. Certain gases require some extra provision for air adjustment, and most upright burners are now so constructed as to permit of this equipment, if necessary.

The mixing chamber is the enlarged portion at the top of the Bunsen tube, and exercises an important function in producing a more intimate mixture of gas and air, and also serves as a mounting for the mantle.

The function of the gallery is obviously for supporting the chimney, globe, reflector or other equipment.

Modern burner design is carried out on the best scientific lines with a view to producing a burner satisfactory for all gas condi-

tions. Adjustable gas checks, automatically mixing air supply, properly proportioned Bunsen tubes and mixing chambers, a shapely exterior construction with the finest material and workmanship, make the modern burner a very effective and artistic appliance (Fig. 4).

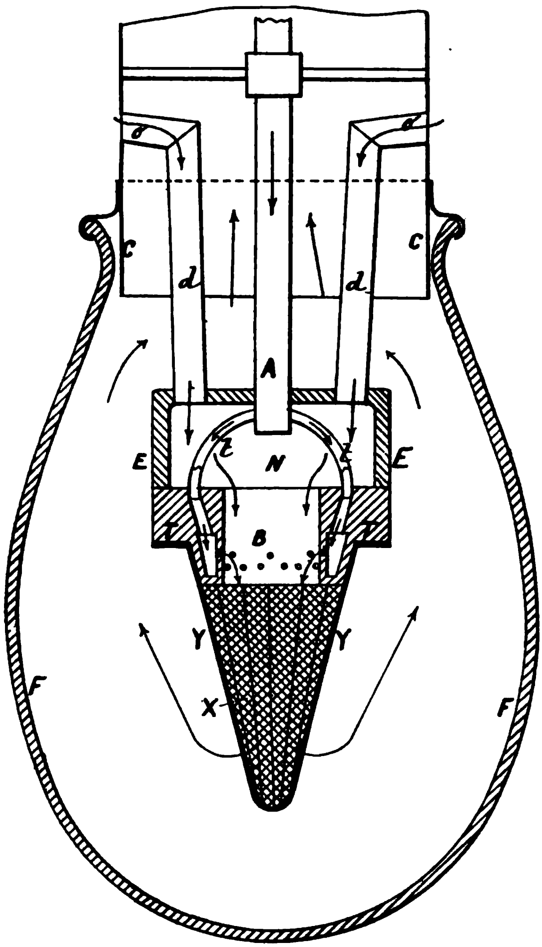


FIG. 5.—Claymond Inverted Lamp.

Inverted Burners

The most important step in the improvement of gas illumination, embodying the use of the Welsbach mantle, has been the

commercial introduction of the inverted incandescent lamp. The reasons which underlie the rapid development of this lamp appear to be *improved efficiency, direct downward distribution of the light, decorative possibilities and more durable mantles.*

The first inverted incandescent lamps were made by Claymond and exhibited in 1882-1883 (Fig. 5). Considerable activity was subsequently shown by inventors, and numerous forms were exploited without commercial success. With the advent of the Welsbach upright mantle, this line of research was abandoned and no developments of any consequence were made for 8 years.

Interest in the inverted light was renewed by the exhibition in Germany of a burner for the thorium-cerium mantle in 1900. These inverted lamps did not meet with marked commercial application in this country, because their designers failed to take into account the principles which modern inverted-burner builders recognize as basic.

The history of the modern inverted burner is confined almost entirely to the development of methods of overcoming the complicated conditions of inverted combustion.

Types. Two general divisions may be made which involve different applications of the principles of combustion.

The first is based on a burner calculated to pre-heat the gas or air, or the mixture; and the other is a type where the construction is arranged to avoid, as far as possible, increasing the temperature of the gases before they reach the point of combustion.

The advantage of pre-heating the gases before combustion is questionable, and prominent authorities may be quoted for and against the increased lighting efficiency to be obtained by this method. It might be inferred that the incandescence of the mantle would be increased by raising the initial temperature of the gases before entering the combustion chamber, but practical results show conclusively that the abnormal rarefaction of the gases due to the increased temperature of the mixture tends to produce the opposite effect.

On the other hand, artificially cooling the gaseous mixture before combustion produces a decrease in the efficiency. Furthermore, the pre-heating or extreme cooling of the mixture complicates the burner construction.

Inverted-burner designers are adopting the medium system, and are constructing a burner so that the gaseous mixture will main-

tain a temperature ranging between the extremely hot gases produced in the regenerative type and the cold gases produced in the cooling type.

In modern practice, inverted-burner construction falls under three general designs.

First. The upright Bunsen, with the tube carrying the gas and air mixture curved through half the arc of a circle (Fig. 6).

Second. The horizontal Bunsen tube, with the mixing chamber curved through one-quarter of an arc (Fig. 7).

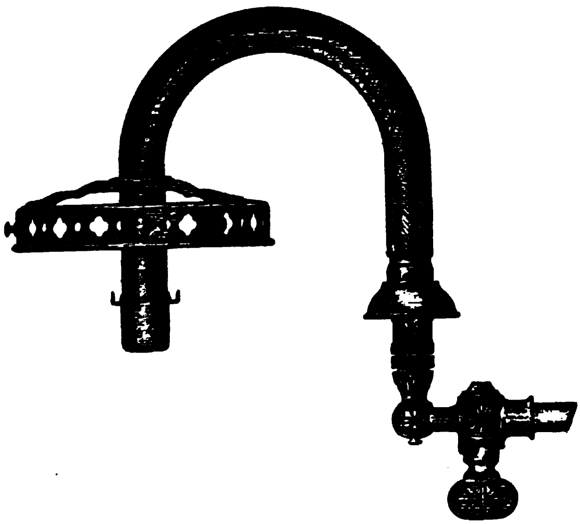


FIG. 6.—Upright Bunsen Inverted Burner.

Third. The vertical Bunsen, with a straight tube, for the delivery of the mixture to the point of combustion (Fig. 8).

Designers recognize as an essential feature of design and function the following general points:

First. The production of a proper mixture of gas and air under all conditions of operation, to insure perfect combustion.

Second. Means for positively preventing flash-backs under all conditions of operation.

Third. Special construction of the Bunsen tube designed to project the gas and air mixture downward to the point of combustion with maximum velocity, in order to overcome the ascending tendency of the mixture.

Fourth. The elimination of obstructions, long circuitous passages for the mixture, or any other features offering frictional resistance to the projection of the gases toward the point of combustion.

Fifth. The protection of the fresh-air supply from vitiation by the products of combustion.

Sixth. An efficient, well-constructed and reliable adjustable gas check.

Seventh. Refractory construction at the burner head.

Eighth. Good mantles.

Ninth. Glassware and reflectors specially selected and adapted for the effective and economical distribution of the light.

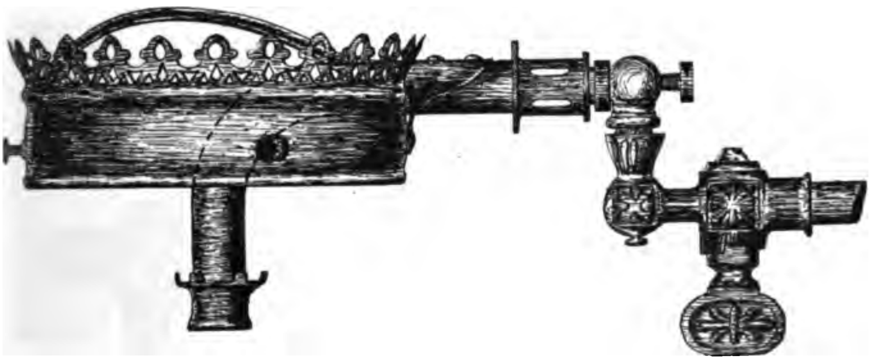


FIG. 7.—Horizontal Bunsen Inverted Burner.

Combustion, as applied to the Bunsen burner, must recognize three basic essentials: (a) the combustible, represented by the gas; (b) the supporter of combustion, represented by the oxygen of the air, and (c) the kindling temperature necessary to start the combustion, applied through the medium of a lighted match, electric spark, or some other heating means. Eliminate any one or more of these three essentials and combustion ceases.

When a certain amount of gas is admitted to the mixing tube of the Bunsen burner, a definite amount of oxygen (air containing oxygen) must be entrained and mixed with it in order to completely consume the combustible constituents of the gas. If the air supply is insufficient to meet these requirements, unconsumed or partially consumed constituents of the gas will be discharged from the burner, either in the form of solid particles of carbon or as noxious

gases. On the other hand, an excess in the supply of air results in a great reduction in the heating power, with its consequent decrease of light, or produces a mixture below the critical point, which may result in a "flash-back."

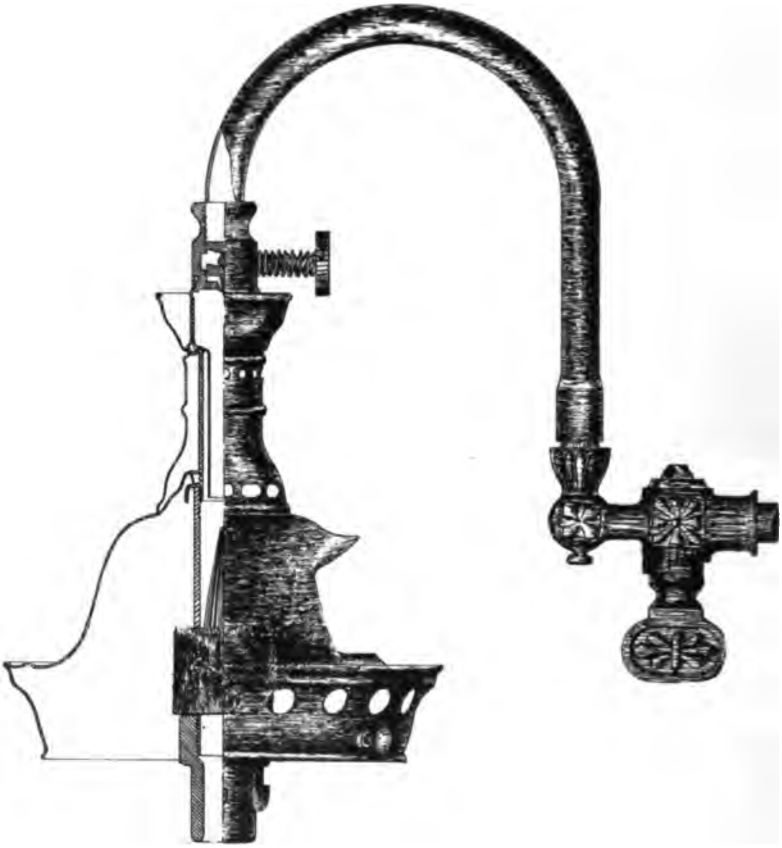


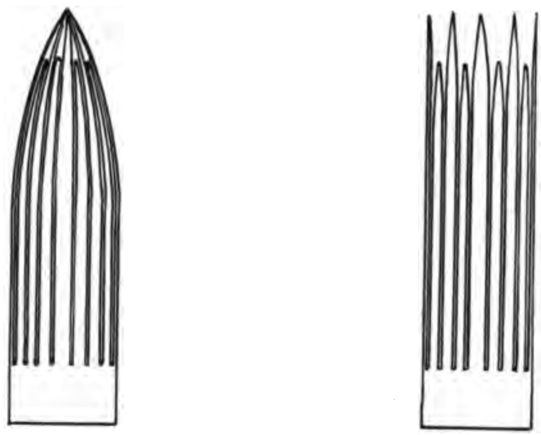
FIG. 8.—Vertical Bunsen Inverted Burner.

The direct cause of a "flash-back" is an explosive action which carries the flame into the mixing tube and sets up combustion at the gas orifice. The usual method used for overcoming the tendency to "flash-back" is by placing a gauze in the burner tube at or near the point of combustion. This gauze serves to maintain the mixed gases in the burner tube at a temperature somewhat below the kindling temperature, and thereby prevents combustion

within the zone it protects. This will be recognized as the principle involved in the safety lamp invented by Sir Humphry Davy.

The use of the gauze for preventing "flash-backs" is sometimes objected to on the ground that it obstructs and materially retards the downward projection of the mixture in the burner tube, and that it becomes clogged with dust and materially cuts off the mixture.

The thermostat (Fig. 9) is a device placed in the lower Bunsen tube of one type of the inverted burner, and performs the function of a gauze without introducing its objectionable features. When



Closed—Cold. Open—Hot.

FIG. 9.—Thermostat.

the lamp is cold the fingers of the thermostat are closed, forming a slitted cone which prevents a "flash-back" on lighting. As the lamp becomes heated the thermostat opens, leaving the Bunsen tube clear for the unobstructed flow of the gas and air mixture. It is so placed in the tube that it is not corroded by the action of the flame, and its automatic movements prevent it from collecting dust. This thermostat is made from a double metal in which each side possesses a different coefficient of expansion; for example, brass and iron. The brass is placed inside, and due to its own rapid expansion when heated causes the curved fingers of the thermostat to straighten out and lie against the walls of the Bunsen tube. On cooling, the brass contracts more than the iron and the fingers resume their original curved position, forming the slitted cone (Fig. 9).

The Bunsen tube, even in its highly developed form, now used in upright burners fails in some essential features when applied to the inverted burner. In considering this problem, it should be noted that the ordinary illuminating gases are lighter than the air and possess a marked ascending tendency even at the normal temperature. When considered in connection with the heated condition

FIG. 10.—Inverted Burner Cut to Show Interior Construction.

of the inverted mixing tube it is seen that this ascending tendency is thereby greatly increased.

The method used for overcoming the ascending tendency of the mixture is to project it downward with sufficient velocity to carry it to the point of combustion without regard to the specific gravity.

The only force available for projecting the mixture downward is that obtained from the velocity of the gas at the check orifice. When it is considered that in many cases the initial gas pressure

is very low, thereby greatly reducing the available force, and also that a certain portion of this force must be given to entraining the air for the mixture, it is obvious that great importance attaches to this function of the inverted burner.

To meet the conditions of varying composition and pressure, or

FIG. 11.—Gas Arc Lamp. Upright for Inside Lighting.

uniformly low pressure in the gas supply, a construction is required embodying all the features of a highly efficient projector for gases. This requires an adjustable check which will give the greatest jet velocity to the gas as it is admitted to the Bunsen; air ports properly placed to give the most efficient entraining capacity; a "raceway" of correct diameter and length to give the mixed gases the velocity necessary to carry them through the mixing chamber and to the point of combustion.

An analysis of the large variety of inverted burners on the market, in the light of these facts and principles, will show a number which do not conform to any specifications except cheapness.

Rapid progress is being made, however, and standardization will ultimately be reached on a combination basis of efficiency, reliability, convenience, durability, pleasing appearance—all with a fair and reasonable cost.

FIG. 12.—Gas Arc Lamp. Upright for Inside Lighting.

Gas Arc Lamps and Clusters

Following the introduction of the upright burner, high candle-power unit requirements were met by forming a cluster of individual burners, with separate gas cocks and chimneys, gathered under a common reflector. These groups of burners were next simplified by the introduction of a cluster of burners controlled by a single gas cock and surrounded by a single globe to replace the individual chimneys. This design of lamp was called a gas arc lamp, and it met with success on account of its simplicity of construction and easy maintenance.

The principal aims in the development of the gas arc lamp have been to produce a unit (Figs. 11 and 12):

First. With a concentrated source of light.

Second. With high efficiency.

Third. Simplicity of operation.

Fourth. Minimum cost of maintenance.

Fifth. Individual gas adjustment for each burner.

No principles differing from those encountered in the individual

FIG. 13.—Gas Arc for Outside Lighting.

burner were involved in the development of this upright arc lamp, although some perplexing conditions were met with.

It was found that in order to approximate the efficiency of the individual burner, the arc would have to be constructed with a "stack" to induce more active combustion at the burner heads. These stacks are made from fused enamel on steel, or from brass in various finishes. Mechanical devices have been evolved for convenient methods for renewing and replacing mantles, removing and cleaning glassware, and innumerable other methods of simplifying and economizing maintenance and up-keep.

Upright arcs have been successfully developed for use outside in places exposed to the action of wind and rain (Fig. 13).

Inverted Gas Arcs

Arcs of the inverted type for both inside (Figs. 14 and 15) and outside (Figs. 16 and 17) lighting are just coming into use, and are being rapidly improved and developed with every prospect of great success.

FIG. 14.—Inverted Gas Arc for Inside Lighting.

Two different methods of construction are utilized in the most prominent types of inverted arc lamps. One in which an individual Bunsen is provided for each mantle (Fig. 14), and the other where a single common Bunsen leads into a manifold head from which outlets are provided for each mantle (Fig. 15). Both of these types are now appearing in various sections, and experience alone will demonstrate the wisdom of the design.

Incandescent Mantles

The incandescent gas mantle was invented by Dr. Carl Auer von Welsbach in 1885 and 1886.

The basis of Dr. Auer's invention is the refractory hood or mantle made from an attenuated mixture of the oxide of thorium with a small percentage of cerium oxide. The cerium, which is present in quantities varying from ½ to 2 per cent, is not an accidental impurity as has been inferred, but is an essential constituent exerting, by very small variations in amount, a marked effect upon the candle-power and quality of the light. The candle-power-cerium

FIG. 15.—Inverted Gas Arc for Inside Lighting.

relation is best illustrated by the curve shown in Fig. 18, in which the candle-power is plotted vertically and the per cent of cerium horizontally. It will be noted that the maximum candle-power is obtained with 1 per cent of cerium, and that a small amount of cerium more or less than 1 per cent causes the candle-power to fall off very rapidly.

This peculiar result may be attributed to the existence at the 1-per-cent point of a solid solution or a definite compound which possesses a higher emissivity than either the thorium alone or the cerium alone.

The manufacture of incandescent gas mantles is a most interesting and complicated chemical process, and by a peculiar coincidence resembles in the delicacy of the hand work involved the close attention to details and the technical supervision required in the manufacture of the incandescent electric lamps.

A brief outline of the materials and processes involved in the mantle manufacture may be of interest.

FIG. 16.

The first step consists in knitting a tubular fabric of open mesh from threads of some combustible organic substance which, after being properly saturated with the thorium solution, may be conveniently burned out, leaving the ash in a more or less adherent mass reproducing the physical form of the original fiber. The selection and preparation of the original fiber is therefore a matter of vital importance. Imperfect fibers or threads, mineral impurities, irregular knitting, etc., all directly affect the quality of the mantle.

The present practice is to use threads made from natural cotton fiber, natural ramie fiber or artificial silk fiber.

FIG. 17.—Inverted Arc Lamp for Inside Lighting.

The cotton thread must be made of a high grade, long staple, Sea Island fiber, uniform in size and free from knots or flaws. The tensile strength of the resulting mantle fiber depends largely upon the length and physical characteristics of the basic fiber. Furthermore, if any knots, flaws, thin places, etc., exist in the threads they are reproduced in the mantle.

Ramie is a natural vegetable fiber made from a substance known as "China grass." The commercial supply of ramie is obtained almost entirely from China, India and Italy. In its crude form the ramie fiber contains large amounts of resins and mineral matter, and its purification is a very difficult and complicated chemical process.

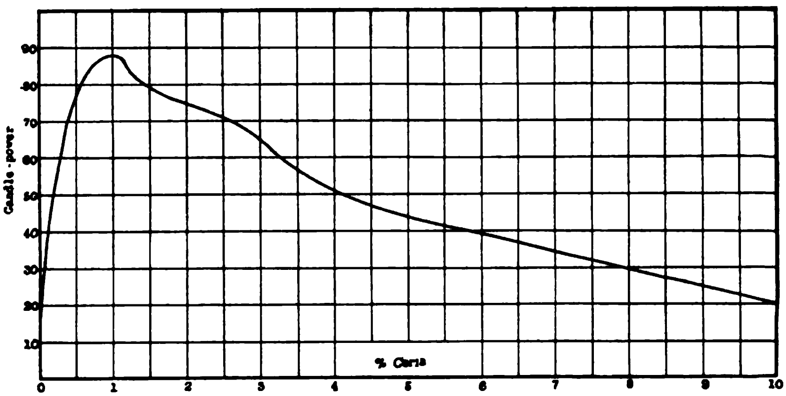


FIG. 18.

Ramie fibers are long compared with cotton and possess greater tensile strength and would naturally be expected to make a stronger mantle. While mantles made from a ramie base do not shrink as badly as mantles made from cotton their tensile strength is somewhat disappointing, especially after being used for a time.

Artificial silk, as the name implies, is an artificial fiber. It is made by dissolving cellulose in some suitable solvent to form a thick viscous solution, squirting this syrup through very fine dies, by great pressure, into some fixing bath. The resultant continuous filaments are then twisted into a thread. This thread may be knitted into mantle fabric and subjected to a special process of treatment for the production of a remarkably improved product. Mantles made from artificial fibers show improved physical strength, no tendency to shrink, no change in quality of light,

and a remarkably small candle-power depreciation, even after several thousand hours of continuous burning.

Saturating is a comparatively simple process, where the thoroughly dried fabric is placed in a suitable vessel and covered with the lighting fluid. As soon as it is thoroughly saturated, the excess of fluid is drawn off and the fabric is put through an equalizing machine piece by piece, in order to bring each mantle to a uniform degree of saturation.

In the highest grades of mantles the amount of lighting fluid used is based upon a careful consideration of the amount of oxide required to produce a mantle of the highest physical and candle-power life.

The lighting fluid is composed of a solution of approximately 99 per cent nitrate of thorium and 1 per cent nitrate of cerium in distilled water. This solution is usually of about 3 parts by weight of water to 1 part by weight of mixed nitrates. While the formula varies somewhat with different manufacturers, the limits are not wide.

The commercial source of the nitrates of thorium and cerium is from a mineral known as monazite. This mineral occurs in commercial quantities only in North and South Carolina and in Brazil. The Carolinas' monazite is found as a sand in the stream beds of the old mountainous districts, while in Brazil it occurs as a beach sand.

Monazite sand is mined on the principle involved in placer mining for gold. The gravel and associated minerals are shoveled onto screens and worked through into sluice boxes, where the minerals of lower specific gravity are carried away by the water currents, while the heavy monazite remains behind. This crude concentrate, carrying from 20 to 40 per cent monazite, is shipped to central plants, where it is further concentrated by the use of Wilfley tables and magnetic concentrators. The final product, as it is delivered to the manufacturer of lighting fluid, contains about 90 per cent of monazite of the following average composition:

Phosphoric anhydride	28%
Cerium oxide	30
Lanthanum oxide	14
Neodymium and praseodymium	16
Thorium oxide	5
Yttrium oxide	2
Iron oxide, calcium oxide, etc.	5
Total	100%

The manufacture of nitrate of thorium from monazite sand is a very difficult and complicated chemical process. It requires from 4 to 6 months to recover the small percentage of thorium and render it sufficiently pure to be used in the manufacture of lighting fluid. The by-products from this process have great scientific and chemical interest but no commercial value, and the thorium must stand the entire expense. The refined thorium nitrate must be chemically pure—free from all traces of mineral impurity and the other constituents of the monazite sand.

The saturated fabric is now fixed for suspension by using asbestos thread to form a loop, then shaped up preparatory to burning out the organic material and converting the nitrates into oxides.

The burning-out process is accomplished by igniting the fabric with a torch and waiting until the organic matter slowly oxidizes.

After the fabric is completely consumed the ash of thorium and cerium oxides hangs in a soft, shapeless, flabby condition, and presents a very remote resemblance to a mantle.

When Dr. Auer first explained his idea for making a mantle to Professor Bunsen that famous teacher replied: "It is extremely doubtful if the ash can be made to hold together." This opinion was based upon Professor Bunsen's knowledge of the general characteristics of metallic oxides, but the oxides with which Dr. Auer was working were notable exceptions. The incandescent gas lighting industry depends upon this remarkable exception.

After the organic matter is completely burned out in the process just described, the soft, flabby ash is carefully adjusted over a blow-pipe. The operator of this device controls levers which raise and lower the mantle, and which adjust the gas and the air supply to the blow-pipes. In some cases the gas is used under a pressure of several pounds to produce the intense flame required, but in either event the adjustment of the flame and the control of the position of the mantle is entirely in the hands of the operator.

Under the influence of this intense blast flame the flabby ash, left when the organic fabric was burned out, is blown (by the proper control of the flame) into the required shape, and is changed from its soft, pliable state into a hard, resilient form. This operation requires greater skill and experience than any other work connected with mantle manufacture.

Coating. The object of this process is to form a protecting elastic skin over the ash to carry it while the mantle is going

through the inspecting, trimming, packing, transportation and installation stages.

This coating, or collodion, as it is usually called, is made from soluble cotton. Soluble cotton is made by the so-called nitrating process in which the loose cellular fiber is treated with a mixture of sulphuric and nitric acids, and a product is formed closely allied to gun-cotton.

This nitrated cotton, after being thoroughly washed and dried, is dissolved in some of the numerous solvents such as alcohol-ether, acetone, etc., and a thick, viscous liquid is produced.

The collodion is placed in suitable vessels, over which the mantles are suspended and into which they are dipped, then transferred to hoods to dry. The mantles are then inspected and packed to meet the great variety of needs of the established markets.

It is estimated that the American market consumes 60,000,000 mantles per year, most of which are standard-sized upright and inverted mantles. Large quantities of mantles are also produced for railroad-coach lighting with Pintsch gas, kerosene lamps, gasoline systems and high-pressure oil lamps.

In the limited allotment of time for this subject, this review must necessarily be brief and superficial, but I have attempted to make it clear to you that the development, growth and future of the incandescent gas-lighting industry is a matter of immense scientific and economic interest.

VI

THE GENERATION AND DISTRIBUTION OF ELECTRICITY WITH SPECIAL REFERENCE TO LIGHTING

By John B. Whitehead

CONTENTS

Principles and Design

1. Interior illumination.
   a. Systems of power supply: generating plants; constant potential; direct current, 2- and 3-wire; alternating current, 2- and 3-wire; alternating current, high voltage single and polyphase; transformers; isolated power plants.
   b. Systems of distribution: 2-, 3- and 5-wire parallel distribution, for incandescent glower, vapor and arc lighting; series parallel distribution; low voltage incandescent lamps on direct and alternating current circuits.
   c. Design of electrical system: Choice of system; regulation of supply system; voltage drop in direct and alternating circuits; permissible voltage variation; size of feeders; diversity factor; number and sizes of branches.
2. Exterior and street illumination.
   a. Systems of power supply: Constant potential and constant current, high and low voltage, direct and alternating; constant-current generator; constant-current regulators and rectifiers.
   b. Systems of distribution: Parallel and series parallel constant potential, for arcs and incandescents. Constant-current series systems for arcs and incandescents. Alternating current to direct current systems.
   c. Design of electrical system: Choice of system. Constant voltage and constant current regulation. Size of feeders. Power loss in series circuits; underground and overhead systems.
3. Meters.
   a. Types of meter.
   b. Accuracy, calibration and inspection of meters.

The Installation of Electric Lighting Systems

1. Interior illumination.
   a. Type of installation. Two- and three-wire. Exposed and concealed wiring. Conduit systems and outlet boxes.
   b. Control. Service connections. Distributing centers. Switches. Protective devices. Subdivision of total copper.
   c. Relative costs.

d. Fire and insurance control. Ground connections.
e. Specifications, drawings and contracts for work of installation, including materials.
f. Tests.

2. Exterior illumination.
a. Type of installation, arc or incandescent, parallel or series. Overhead or underground systems. Insulation.
b. Control. Automatic cut-outs. Protective devices, lighting arresters.
c. Municipal restrictions. Underground construction and cables.

2. Cost of operation.
a. Cost of electric power.
b. Systems of rates of sale of power; flat rates; maximum demand; two-rate systems.
c. Contracts for purchase of power.

Principles and Design

Electricity for lighting may be taken from any type of generator. The earliest types of generator were developed to meet the requirements of lighting apparatus. With the introduction of other applications of electricity generators have been designed with characteristics to meet particular purposes, but it is probable that every operating generator furnishes more or less current for lighting. In modern installations, in which a large portion of the total capacity is consumed in lighting, the generators are designed with special reference to the regulation required by lighting service. Such generators are of various types, the extremes being the smallest continuous-current dynamo of the isolated plant for a single building, and the modern high-power (20,000 kw.) alternator of the city central station.

The proper circuit conditions for electric lighting are either constant potential or constant current. The general problem of central-station design to meet these conditions involves a knowledge of the various sources of energy, types of prime movers, generators, control and regulating apparatus, and is distinctly within the province of the present-day electrical engineer. The electrical phase of the problem of the illuminating engineer will only in extremely rare instances contain the questions of prime movers, generators and station design. In general his concern, certainly in interior illumination, need go no further back than the available service mains. At this point he need only recognize the type of service, know what regulation he may demand, and be able to

draft a service contract for his client. From this point inward he must be able to design the distributing system electrically and mechanically, with due regard to fire hazard and conformity to local regulations. He must be able to draft a specification and prepare drawings for an installation which shall amply secure for his client a completed and tested lighting system for a definite price. The exterior problem requires a somewhat wider knowledge of the principles of distribution, but will rarely, if ever, approach the station nearer than, say, a constant-current regulator. In brief, the illuminating engineer can generally assume that the electrical engineer will furnish him with constant pressure or constant current. The electrical problem of the former is to know the limits of this constancy, and to be able to design, install and test the proper distributing system. Should the illuminating engineer ever desire to extend his knowledge to the engineering of generating equipment, many excellent treatises on the subject are readily available, and it does not appear desirable, in the short space allotted here to the electrical problem of the illuminating engineer, to devote more than occasional mention to a kindred topic of wide extent and well treated in the literature of the subject.

1. *Interior Illumination*

(a) **Systems of Power Supply.** The commonest class of public power supply for interior lighting is at constant potential. In the hearts of cities it is usually in the form of continuous current supplied by an underground three-wire interconnected network of mains. This network is fed, over underground feeders connected to the mains at various points, from rotary converters or motor generators in one or more substations. The general plan of such a network is indicated in Fig. 1. These machines are operated by alternating current which is generated at voltages up to 15,000, or even higher, in central stations at some distance from the substation centers of distribution. The voltage of these networks is 220 to 240 between two so-called "outside" wires, and 110 to 120 volts between either outside wire and a third or "neutral" wire which is usually kept at the potential of the earth, or "grounded" by connecting to an underground system of water pipes, or by other methods. Most interior lighting devices are designed for voltages in the neighborhood of 110, and the aggregate load is divided as uniformly as possible between the two sides

of the three-wire network. In this way the two halves of the load are connected in series, and the distribution for 110-volt service is accomplished at 220 volts, with great saving in the amount of copper, since, at a given loss and distance, the amount of copper necessary varies inversely as the square of the voltage. The use of the neutral conductor, however, reduces the amount of this theoretical saving. The neutral conductor is made necessary by the facts that the component parts of the load on the two sides of the system are often separated by some distance, and especially that the two sides of the system are never exactly equally loaded.

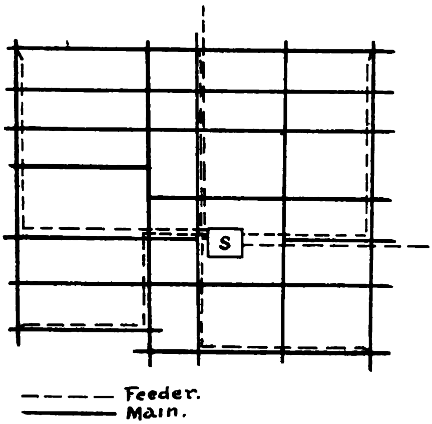


FIG. 1.

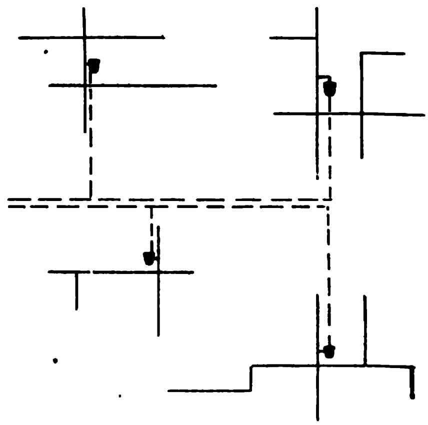


FIG. 2.

FIG. 1.—Direct-Current Underground Network.
FIG. 2.—Outlying Alternating-Current Distribution.

The excess current of the more heavily loaded side flows back to the substation over the neutral conductors of the mains and feeders. This conductor therefore only carries the difference in the current of the two sides of the circuit, and in a large system with average balance of load between the two sides of from 2 to 5 per cent, its cross-section may be considerably less, say one-half that of the outer wires. This system therefore requires a generator connection at a point midway between the potentials of the outer terminals. This may be accomplished by operating two generators in series and connecting the neutral to their junction. By the use of various auxiliary devices single machines may be constructed for supplying three-wire service.

The cross-section of the main conductors of such a network may aggregate several million circular mils, divided into lead-covered cables of 1,000,000 or 2,000,000 c. m. each. The feeder cables are usually somewhat smaller, with neutral one-half the section of the outside conductors. These feeders are provided with a small insulated strand leading back to the station, which serves to indicate in the station the potential at the network. The voltage drop in the feeders varies from time to time and may be as great as 10 per cent.

In locations at some distance from the central station or sub-

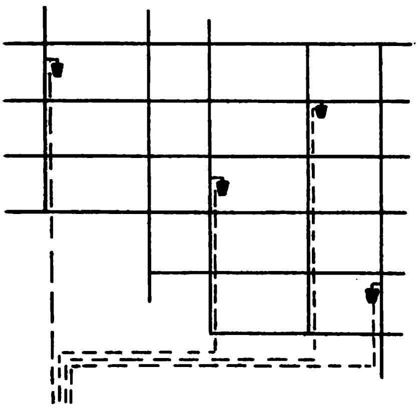


FIG. 3.

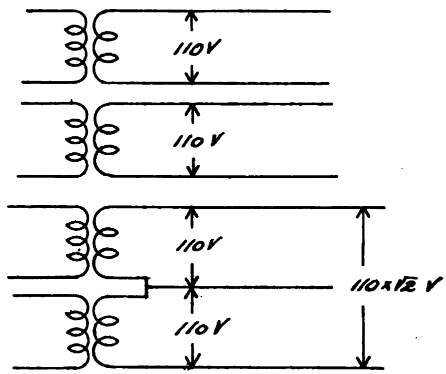


FIG. 4.

FIG. 3.—Alternating-Current Secondary Network.
FIG. 4.—Two-Phase Three- and Four-Wire Systems.

station power is transmitted as high-voltage alternating current, and the voltage lowered by transformers which feed into the consumers' circuits. For the extreme outlying districts with widely scattered consumers, each is often fed from a single small transformer located at the property line, and supplying power over two wires only. In intermediate regions where the consumption is fairly dense several consumers may be fed from the same transformer, as indicated in Fig. 2. For still denser regions, beyond the reach of the continuous-current network, a secondary alternating-current network fed by several transformers at different points is sometimes formed (Fig. 3). In each of these cases the three-wire system is commonly used with 220 to 240 volts on the outer wires, and the neutral connected to the middle point of the transformer

secondaries. Both the primary and secondary circuits in this class of supply are usually carried overhead, though not invariably.

The modern large central station generates at 25 cycles, three-phase. This frequency is the best for transmission and for transformation to mechanical power. It is not, however, well adapted to either arc or incandescent lighting, although there are many instances in which it is used for the latter. Economy of transmission copper and the superiority of the polyphase motor for power service result in the general use of three-phase instead of single-phase primary circuits.

For lighting from such systems motor generators are often used for changing from 25 to 60 cycles, the latter being the standard frequency for alternating-current lighting.

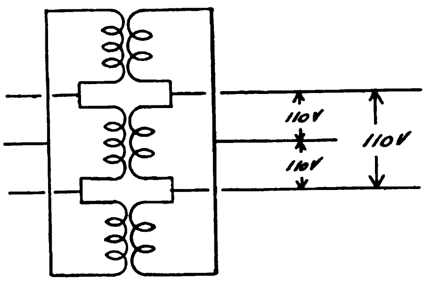


FIG. 5.

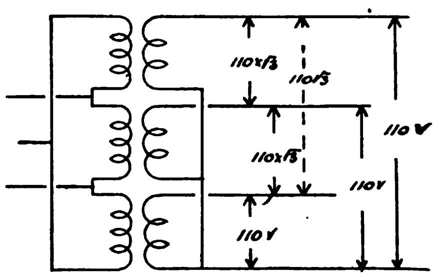


FIG. 6.

FIG. 5.—Three-Phase Three-Wire System.
FIG. 6.—Three-Phase Four-Wire System.

The 60-cycle generator for city lighting operates usually at some voltage between 2200 and 2600. Since there is always a market for power also, it is commonly of two- or three-phase type. Secondary lighting circuits at 220 to 240 volts are obtained from the polyphase primaries by transformers connected in various arrangements. If the service is for lighting only, single-phase secondaries only are needed, and single transformers for the separate loads are connected to the various phases, and in such manner that the aggregate load is as nearly as possible divided evenly among the several phases. In some instances, however, there is a power load requiring small motors which cannot be operated at the high primary voltage. These moderate-size motors are also most satisfactory in the polyphase type. The secondary distributing system must therefore be polyphase, and this is accomplished

by various transformer combinations, resulting in three-, four- and even five-wire secondary systems. Figs. 4, 5, 6 and 7 show several of these combinations. Lighting circuits may be taken from any one of the branches of such a symmetrical system. This results, however, in placing both lamps and motors on the same transformer. Since the alternating-current motor often takes a starting current several times as great as its normal running current, the starting of the motors frequently results in a momentary fluctuation of voltage which is noticeable at the lamp. For the most satisfactory results the lighting and power loads should be on separate transformers, as the greater part of the voltage disturbance occurs in the secondary distributing circuit and in the transformer itself.

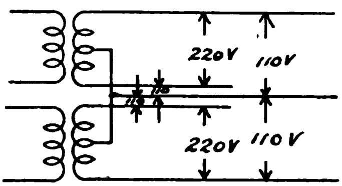


Fig. 7.

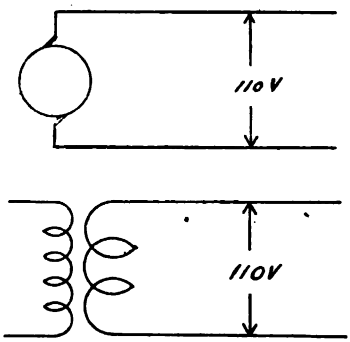


Fig. 8.

Fig. 7.—Two-Phase Five-Wire System.
Fig. 8.—Two-Wire Distribution.

An important type of supply system is the so-called isolated plant of a single large building or factory. These plants are either steam-, gas- or water-driven, and generate current of the class and voltage required at the lamp. Thus many of the earliest plants are equipped with 110-volt, two-wire continuous-current compound generators. Those of more modern design, however, have 220-volt three-wire generators, as the extent of the distributing system is usually sufficient to demand the resulting economy in copper. This type of plant for lighting alone constitutes as reliable a source of supply as can be obtained. Properly chosen, the generating plant will give as constant voltage regulation as may be desired, and satisfactory performance of the lamp will then depend only on the design of the distributing system. Usually, however, these

plants must also furnish power. Little trouble is caused if the motors are of moderate size and the power load fairly constant. The elevator or other similar motor, however, with its large starting current will usually cause serious voltage fluctuations unless special provision is made for its fluctuating load. The most approved equipment for this purpose is the storage battery with "booster" generator; the battery automatically charges at values of load under the average and discharges when the elevator motors require their greatest currents. This equipment also serves to equalize the demand on the generators between the light and heavy portions of the daily load curve, the battery charging during the morning hours and discharging as the lighting peak comes on.

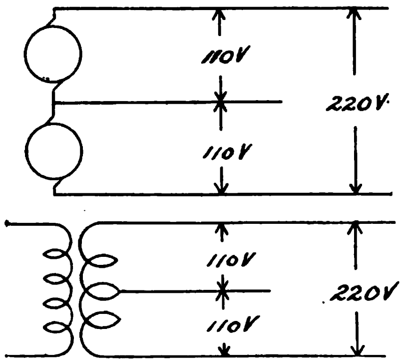


FIG. 9.—Three-Wire Distribution.

(b) **Systems of Connection.** Except in rare instances all interior electric lighting is obtained from lamps designed for constant voltage. The range of this voltage between 110 and 130 volts is that within which the incandescent lamp can be most satisfactorily constructed. This has probably been the most important influence in fixing this practically standard value for the voltage of low-tension distributing circuits. The various other types of lamp for interior service have, therefore, naturally developed with conformity to this voltage, or to double its value, as obtained from the outer wires of the three-wire distributing system.

Incandescent lamps, therefore, for interior illumination may be fed from the simplest type of two-wire distribution, shown in Fig. 8, or they may be connected between either outer wire and the neutral of a three-wire system, as in Fig. 9, or they may be

connected across any branch of a secondary polyphase lighting and power network, as already described. The usual voltage in these cases is between 110 and 130. Incandescent lamps for operation on 220 volts are obtainable, and are sometimes used on a 440-volt three-wire system to secure the benefits of the higher voltage for distribution. These lamps are inefficient and less rugged than those of lower voltage, and this system has not been generally adopted.

Obviously the incandescent lamp may be supplied from either alternating or continuous-current circuits. Several exceptions to this statement must be noted, however. The life of the tantalum lamp, for reasons not yet understood, is shortened when used on alternating circuits; the amount of this shortening is about 50 per cent when operated at 60 cycles. In many instances it is possible to detect a flicker in lamps operated from 25-cycle circuits; this is most noticeable in lamps of low candle-power and high voltage in which the filament is necessarily of small diameter. Nernst lamps operate on 110- and 220-volt constant-potential alternating circuits. A glower adapted to continuous current has been developed but has not met with success. Such lamps, therefore, are adapted to the several types of alternating-distributing systems only.

The mercury vapor lamp is best adapted to constant-potential continuous-current systems, but is also manufactured for alternating service. It may be constructed for a wide range of voltage, but is commonly manufactured for 110- and 220-volt circuits.

Interior illumination of stores, factories, etc., by means of arc lamps is quite common, and in such instances the lamps are operated from constant-potential circuits. Although the arc lamp in its best form is a constant-current device, constant-current circuits are usually of a voltage too high for introduction into buildings. Multiple or constant-potential arc lamps have, therefore, been developed, and it is now possible to secure an arc lamp suitable for any type of available supply system. Thus single arc lamps may be supplied from either 110-volt side or from the 220-volt outer wires of either a continuous or an alternating three-wire distributing system. Lamps for 110 volts continuous current may be operated singly or two, four and five in series from 110-, 220-, 440-, 550- (railway) volt circuits. Lamps may be operated singly, by means of compensators or transformers from alternating circuits of any voltage or frequency.

Incandescent lamps are frequently connected several in series, where the available voltage is higher than that of the lamps. The most familiar instance of this method of connection is found in the cars and buildings of the street-railway system operating at 550 volts. The introduction of the efficient metallic filament has led to an extension of this method of connection, as applied to low-voltage, low candle-power incandescent lamps operating from 110-volt circuits. This method of connection has arisen from the desire for a lamp of lower rating and more durable construction than the 25-watt, 110-volt tungsten. Standard-base tungsten lamps may now be had for any voltage below 130, and lamps of 1.25-watt consumption in 10-, 15- and 20-watt sizes and at voltages from 10 volts upward are standard with manufacturers. The obvious objection to this series parallel method of connection is the fact that the failure of one lamp cuts out the others in series with it. These lamps are especially hardy, however, owing to their short, stout filaments, and when once in place in rigid sockets the plan is well adapted to long passageways and other areas requiring four or more units of low intensity without independent control. Four 28-volt, 10-watt lamps in series on a 115-volt circuit is a very satisfactory instance of this type of connection. Ten 10- or 12-volt, 5-watt lamps in series are sometimes used for sign lighting, but the arrangement is not satisfactory owing to the result consequent upon the failure of one lamp.

Multiple operation and independent control of low-voltage lamps on existing multiple wiring is possible on alternating circuits by the use of transformers and "economy coils" or auto-transformers. With the use of the latter it is possible to operate the lamps in series, and the failure of one lamp will not affect the others.

(c) **Design of Electrical System.** The designer of interior illumination will rarely if ever find it necessary to extend the system of electrical conductors beyond the property line. In cities, for example, the source of supply will be either an underground continuous-current three-wire network with connections from a nearby manhole available at the building line, or an overhead secondary alternating-current line at a greater or less distance, or in many of the larger problems the power supply will be in or very near the building itself in the form of an isolated plant.

Considering, first, the source of supply, the careful engineer

will consider (a) its capacity, (b) its reliability, (c) its voltage regulation, and (d) its distance and the class of current, i. e., whether continuous or alternating current, and if the latter, its frequency and voltage. The capacity of the source of supply, including the transmission conductors up to the point from which the new lighting load is to be taken, must be sufficient to ensure satisfactory and continuous operation of all the loads upon it. Moreover, the application or removal of any individual load should be without disturbing effect on any of the others. The questions of capacity and reliability are not apt to arise in connection with an underground continuous-current network, or with an individual isolated plant constructed especially for the system under design. Also, in the commoner instances of alternating-current secondary-distributing systems, since the transformers are the property of the supply company, the question of capacity will be taken care of by them. The question of reliability in such systems assumes importance when the transformers are at the end of long feeders, particularly if the latter pass through open country for any distance. Suburban lighting from the best class of supply company is often subject to interruption from line troubles due to wind, snow and sleet, and lightning. For large installations, where even a short interruption is to be avoided, these considerations may be sufficient to justify an isolated plant. Generally, however, occasional brief interruptions in localities where this class of service is the only one available can be tolerated, and the engineer need only satisfy himself that the overhead lines are of approved construction and protected by lightning arresters of design and location dictated by the best present-day knowledge of this imperfectly understood portion of the problem. A committee of the National Electric Light Association is now engaged in an effort to standardize the methods of installing the various types of distributing system. At this time definite recommendations have covered secondary-distributing systems only, and are contained in a report to the Association at its convention in May, 1910. The work of this committee when completed will furnish an excellent reference for all questions of overhead lighting wiring. Should the engineer find it necessary to specify and install his own transformers, the questions as to the methods of installing them, together with their fuse blocks, are considered at length in the report mentioned above. The transformer capacity and subdivision, in its relation

to the installation, depend on the time distribution and concentration of the connected load. These two elements are usually combined in the "diversity factor," or the ratio of the sum of the maximum demands of the several consumers to the maximum demand which actually results from their combined service. For transformers in residence lighting this factor is about 3, in commercial lighting from 1.6 to 1.1.

Speaking generally, transformers may be operated for an hour or two at 50 per cent over their rated capacity, and for short intervals at 75 per cent or 100 per cent. On account of the short distances to which low-voltage alternating current may be transmitted, transformers on poles rarely exceed 15 kw. in capacity, and 30 kw. is about the limit in size for transformers for lighting only.

The voltage regulation of the supply system, next to constancy of service, is the most important factor for satisfactory lighting. Too often the engineer has to be content in this particular with what he can get. In the present state of the art it is rarely possible to secure from a supply company any statement or guarantee as to the limits of fluctuation of its voltage. Probably the most constant voltage obtainable is that in the best type of isolated continuous-current plant, as found in a few modern office buildings with special provision for motor loads. In this case the feeders are all short, and the regulation approximates the practical constancy obtainable in compound generators. Often, however, the isolated plant has too little capacity, and carries both motor and lamp loads without special regulating apparatus. In such cases the regulation is very poor.

The underground 220-volt, three-wire continuous-current network of the best type of city plant yields excellent regulation. Such a system comprises a close network of mains, often comprising several 1,000,000 circular-mils cables. The voltage in this network is maintained constant by connecting it at various points with feeders from the station. Potential wires, as already mentioned, are also run to the station and indicate the voltage throughout the network. The voltage on the feeders is varied according to the needs by connection to several sets of bus-bars of different voltages, operated from separate machines, or through boosters and other regulating devices. The method is indicated in Fig. 10. The load changes of such a system, owing to its size, are quite

uniform, so that voltage adjustment at any point of the network is simple. In such a system a daily constancy within 1 or 2 volts is obtainable.

Alternating-current secondary-distributing systems do not, as a usual thing, afford as satisfactory voltage regulation as the continuous-current system. The drop in the primary wires is rarely a disturbing factor, since this is compensated for in the station, and that in the transformer may be less than 2 per cent on non-inductive incandescent-lamp load. A serious drop due to inductive reactance, however, occurs in the low-voltage secondary circuits, and limits their length to comparatively short distances. For this reason secondary networks, commensurate in size with those of the continuous-current system, are not used. In such

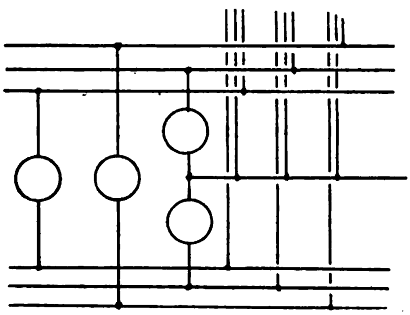


FIG. 10.—Station Connections Direct-Current Feeders.

an alternating-current network a transformer fed from a separate pair of primary wires constitutes a feeder corresponding to that of the continuous-current network, and since alternating-voltage regulation is simpler, the station apparatus of this system is less elaborate and, therefore, cheaper. The transformers must be close together, however, owing to the drop in the secondary circuits, and this condition is greatly aggravated in the fairly common event of one transformer getting into trouble. These facts are sufficient to have restricted the alternating network to comparatively limited areas. When several transformers are connected to the same primary circuit, station control compensates for the variable drop of changing load; obviously that this arrangement be satisfactory to all consumers, they should all have approximately the same type of load variation. It will be thus seen that the voltage regulation of alternating sources of supply may be good

or bad depending on the type of control at the station, the number of consumers on a line, the particular way in which these consumers vary their demand, etc. If the lighting circuits are also used for motors, it is still more difficult to secure good regulation. In the better classes of service momentary variations of 1 or 2 volts in 110 should not be cause for complaint. As the load goes on the voltage is raised at the station either automatically or by hand, and this may cause an extreme daily variation of 3 or 4 volts. Departing from the best class of service, it is possible to find almost any degree of poor regulation in lighting circuits. In these days, however, a total daily variation greater than 5 per cent should not be tolerated from a company professing to give first-class service.

With the voltage variation of the supply system given, the engineer must design his distributing system so as to add as little voltage variation as possible, and so keep the voltage at the lamp as nearly constant as the source of supply will permit. The principles involved in this design are simple, and the problem is usually the very indefinite one of a decision as to what additional drop to allow in order to secure a low cost of the distributing system. With continuous current the application of Ohm's law in one of its several forms will determine the size of conductor for the chosen voltage drop. Temperature variation of resistance, however, must be duly considered. If many calculations are to be made it is usually worth while to make use of tables giving relations between current, voltage drop, distance, etc., such as may be found in Hering's Wiring Computer and other like works. In most cases, however, it will be more satisfactory to make calculation using resistance tables with temperature factors clearly given.

The loss or drop in voltage in alternating-current circuits is due to resistance and reactance. The resistance may usually be that given by any wire table with temperature correction. The reactance drop is caused by the electromotive force induced in the circuit by its own alternating magnetic field. This electromotive force is therefore proportional to the current, and to the frequency, and to the self-inductance, which depends on the length, the separation and the size of the conductors. The mathematical expression for the reactance in ohms is $2\pi NL$, and for the reactance volts $2\pi NLi$, N being the frequency, L the self-inductance and i the current. The resistance and reactance volts are both propor-

tional to the current, but differ in phase by one-quarter of a period so that the total drop in volts is the square root of the sum of the squares of the resistance and reactance volts. While the resistance decreases rapidly with increasing size of wire the reactance decreases very slightly, consequently there is in alternating-current distribution an early limit to the improvement in voltage regulation by increase in the size of conductor. It is for this reason that low-tension alternating circuits must be short. The resistance and reactance at 60 cycles per mile of a circuit of two No. 5 wires, 24 inches apart, in ohms, are 3.24 and 1.4; for No. 00 the values are .8 and 1.24; it is seen that for sizes in this neighborhood little is gained by increasing the size of wire. Complete tables of resistance, reactance and impedance volts for various sizes of wire, separation, frequency, are now readily available, so that calculations may be quickly made. Attention to the reactance drop is especially necessary in designing overhead service connections with space separation, and must not be lost sight of even in interior wiring where the two sides of the circuit are close together inside one conduit. For example, two No. 0 wires in a 2-inch conduit may easily have an average interaxial separation of 1 inch; the reactance per 1000 feet is about .1 ohm or one-half as great as the resistance; the impedance is therefore .224 or 25 per cent greater than the resistance.

Secondary-distributing networks must therefore have transformers connected at fairly frequent intervals. A common method is to run three-phase primaries, supplying three or four city blocks from one phase through three transformers with their secondaries connected to a common three-wire main. The next three blocks go on the next phase, etc., preserving the balance as far as possible. Speaking broadly high-class secondary distributing or service circuits should not exceed 400 to 600 feet in length, or between transformers.

In calculating the wiring for any installation two types of voltage drop must be considered, viz., that due to the gradual daily increase of the total load, and that due to the sudden cutting in or out of a portion of the total load. The former occurs gradually and principally in the mains from the supply system, and in the "risers" and distributing feeders. If the maximum load on all branches is definitely known, the voltage drop due to this cause may, of course, be kept within any limits by proper choice of con-

ductors. A wide range of variation of this kind is very objectionable. If the lamps are chosen for the high voltage, their luminous efficiency is impaired as the load goes on; if for the low voltage the life of the lamps used at light loads is shortened. As this type of variation is gradual it is not noticeable, and too little attention is given it in design. The second type of voltage variation is necessarily less in amount than the first, and is principally objectionable in causing a momentary fluctuation of light from other burning lamps. This disturbance is reduced by designing so that the smaller part of the total permissible drop takes place in the mains and principal distributing feeders, and by increasing the number of branch feeders. A change of 1 per cent in the voltage on a tungsten lamp causes a variation of 4 per cent in its candlepower. Fluctuations of this nature, therefore, are to be particularly guarded against in those cases where there is frequent cutting in or out of large numbers of lights.

It is difficult and scarcely necessary to fix an absolute limit to the permissible voltage variation on an incandescent lamp. Satisfactory illumination is given by the 120-volt tungsten lamp over a range of 4 volts or more than 3 per cent; in fact, a given lamp is now rated for 3 voltages covering this range. The important consequences of this variation are the effects on the efficiency and life of the lamp, rather than on the illumination. Speaking generally, with a supply system constant to within 1 or 2 per cent, very satisfactory service will be given if the maximum voltage drop inside the service connection be limited to 3 per cent. Of this the smaller part should be in the service wires and larger branches. A greater drop than this may be allowed when the greater proportion of the lamps are operated together, and so cause approximately a fixed drop in the service wires. With the entire load connected as one unit, i. e., with no independent operation of single lamps, any amount of drop in the service connection may be allowed, by a proper choice of lamp. The calculation of the size of service wires, feeders and branches to meet the requirements of voltage is thus a simple matter of distances as soon as the location of the individual outlets and sizes of lamps are fixed.

The usual installation begins at the service wires, which may be either overhead or underground; these are generally 220-volt, three-wire, carried directly to a center of distribution, which may be of any degree of elaboration. A simple iron box containing

a main switch and fused branch cut-outs suffices for a small residence. For large installations a switchboard having panels for the main connection and individual feeders, as found in the largest buildings, may be required. From this center feeders run to distributing centers in various portions of the building. From these distributing centers sub-feeders are often taken to smaller local centers, though, more commonly, so-called branch circuits lead directly to the lamp outlets. The number of feeders and sub-feeders is regulated by the height and the floor area of the building. For great heights individual feeders for one or more floors may be necessary. Generally, however, several floors may be fed from one riser. For large areas, sub-feeders from the distributing to local centers may often be used to advantage. The three-wire system. is carried to the centers where branch circuits are connected. Probably the most important factor in determining the number of feeders is the permissible length of branch circuit. The "National Electrical Code" limits the lamp capacity of a single branch circuit to 660 watts. This figure was chosen as representing twelve 55-watt carbon lamps. Under this rule it is now possible to install twenty-six 25-watt tungsten lamps, although such a plan is not advisable. Further, no wire smaller than a No. 12 B. & S. should be used for the branch circuits. At 115 volts, 660 watts represent about 5.5 amperes, and the resistance of No. 12 wire is 1.62 ohms per 1000 feet. An average length of 50 feet of this circuit would therefore cause a drop of 1 volt. With good regulation of supply system and ample copper in service wires and feeders, branch circuits may sometimes have a length of 100 feet, but this should be the maximum of conservative practice. Exceptional cases may be met by increasing the size of the branch circuit. A radius between 50 and 100 feet, therefore, marks the area to be fed from one center or feeder connection. In small buildings, such as residences, therefore, no feeders are required, all branch circuits starting from a suitable distributing board where the service wires enter. In larger buildings the density of the load on various floors will determine whether more than one floor may be fed from one feeder. The low consumption of tungsten lamps will usually permit two or three floors to a feeder or a riser, with 10 or 12 branch circuits to a floor. In such a case it is advisable to place a distributing board on each floor, and not extend the branch circuits from a center on one floor to outlets on floors above and below.

With all feeders brought back to the service connection, which should be located as near the mean center of load as possible, it is a simple matter to calculate the voltage variation on any lamp with all lamps burning. With a fixed limit of variation, this condition will usually call for larger feeders and service wires than necessary. A study of the particular problem only can determine the probable maximum number of lights to be operated at one time. For residences this number will rarely exceed one-third to one-half of the total, while in office buildings, churches, theaters, etc., the total connected load may often be in operation at one time. It is only in exceptional cases that the cost of copper in the feeders is a sufficiently large proportion of the total cost to warrant the reduction of their size. No great increase in cost will generally result from designing service wires and feeders to the end that the operation of the maximum connected load will only cause the permissible voltage variation on the lamp most unfavorably located.

2. Exterior and Street Illumination

(a) **Systems of Supply.** Exterior illumination may be taken from any available source of supply. The use of constant-potential continuous-current service is limited to loads concentrated within a small area, owing to the fact that the distributing losses mount very rapidly for any considerable distance. Instances of this type of supply are electric signs from 110- to 220-volt mains, multiple arc lamps in front of buildings or stores, and street arches supplied from 550-volt railway circuits, the lamps being connected in series-parallel.

Constant-potential alternating current at 2200, 4400 or 6600 volts is probably the most common type of exterior supply circuit, and it may be utilized in various ways for exterior lighting. It may be simply transformed to low-voltage, constant-potential service or to high-voltage, constant-alternating current for series arc and incandescent circuits, or to high-voltage continuous current by means of the mercury rectifier. The last mentioned is perhaps the most satisfactory of all methods of arc lighting.

For many years constant-continuous current, series arc circuits were supplied from Thomson-Houston and Brush constant-current generators. Many instances of the latter type of installation are still in operation, and these machines operate with as high voltage

as 13,000 with currents of 5 to 10 amperes supplying upwards of 220 lamps. These excellent machines, after a highly honorable record, are now being rapidly supplanted by constant-potential to constant-current transformers fed from 2200 volts constant-potential alternating circuits and supplying on the secondary side constant-alternating current. These transformers are equipped with one stationary coil and a movable coil which automatically shifts its distance from the fixed coil to meet the demands of the load.

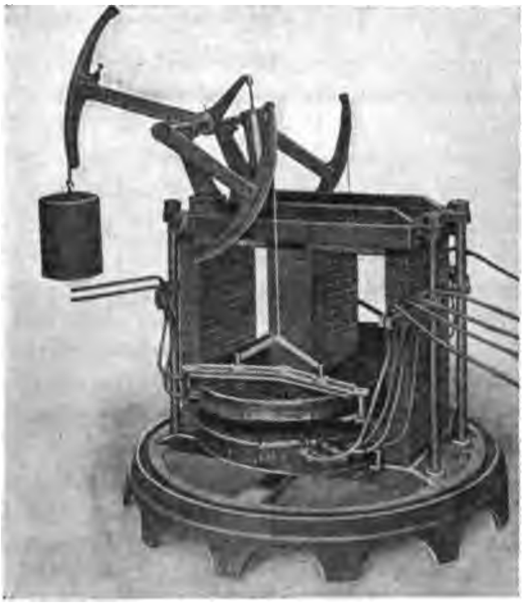


FIG. 11.—Constant-Current Transformer.

In a transformer under load there is a repulsive force between the two coils. In ordinary constant-potential transformers this force is held in check by the close-fitting iron of the magnetic circuit. In the constant-current transformer this force is allowed to act, free motion of the secondary away from the primary being allowed by providing a greater opening in the magnetic circuit than is required by the cross-section of the coils. But a separation of the two coils, due to a rise in current, is accompanied by a fall in the secondary voltage, since a portion of the magnetic field set up by the primary leaks across the gap between the coils and so

does not pass through the secondary. The tendency to a rise in current is thus checked by a fall in voltage. By means of suitable counter-balancing of the weight of the movable coil, and by other auxiliary devices, the transformer regulates very closely for constant current, and arc circuits may be taken directly from their secondaries.

Fig. 11 shows a picture of this transformer. More satisfactory, however, is the series continuous current arc circuit, which may be had by combining with the constant-current transformer a mercury-arc rectifier. The combination gives excellent constant

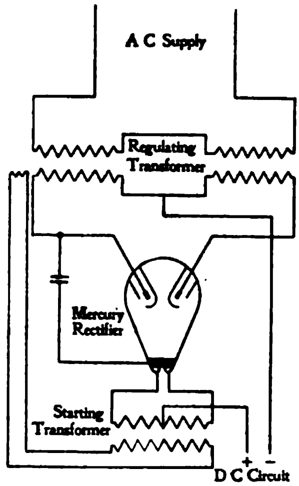


FIG. 12.—Direct-Current Series Arc Rectifier.

continuous current regulation. The method of connection is illustrated in Fig. 12, and the apparatus provides a very reliable means of transformation between constant alternating-potential and constant continuous current. These equipments are available for any voltage between 220 and 13,000, and for any standard of frequency. They may be had in sizes supplying as many as 75 lamps.

(b) **Systems of Distribution.** Arc lamps may be operated from any available source. Their operation on low-voltage, constant-potential circuits is less satisfactory than on a constant-current circuit. The alternating-current multiple lamp is the most unsatisfactory of all, but its use is often justifiable in outlying dis-

tricts with widely scattered lights. The constant-current series method of connecting arc lamps is the most common of all, and the series circuits may be either alternating or continuous current with preference for the latter. These circuits cover wide expanses of territory, and since the connection from lamp to lamp is by one conductor only the distributing system is simple and may be looped in various directions.

Exterior lighting by incandescent lamps may also be adapted to any class of service. For condensed loads, such as signs, it is possible to use the multiple connection from low-voltage circuits using standard lamps. Low-power, low-voltage lamps must be connected two or more in series on continuous-current circuits; on alternating circuits the use of small transformers or economy coils will avoid the undesirable series connection. Street lighting is sometimes accomplished by the series-parallel connection of incandescent lamps on railway circuits or other available constant-potential lines, but the most acceptable system for distributed and uniform lighting by incandescent lamps is the series connection of a number of these lamps across constant-potential high-voltage alternating circuits, or in constant-current circuits, either alternating or continuous. On constant-potential high-voltage service the lamps are shunted by small reactance coils, so that the circuit is continuous, and the voltage consumed by reactance if an individual lamp should fail. Tungsten lamps for this system are to be had with ratings of 1.75 to 4 amperes, and from 8 to 40 volts, so that it is possible to operate 260 such lamps in series on 2200-volt circuits. It is claimed for the system that operation is still satisfactory with 20 per cent of the lamps broken or out. The series connection of tungsten lamps may also be operated at constant-alternating current by use of the constant-current transformer already described. By this method upwards of seven hundred 30-watt, 3.5 or 6.6 amperes, lamps may be operated in series. In this system each lamp is equipped with an insulating film which withstands the lamp voltage but breaks down if the lamp fails, thus preserving the continuity of the circuit. The transformer adjusts automatically for the lowered voltage.

(c) **Design of the Electric System.** Constant-potential regulation is obviously much less important in outside than in inside lighting. Incandescent lamps employed in this class of service are comparatively few, and the objections to voltage fluctuations are

practically limited to the effect on the life of the lamps. The arc lamp is essentially a constant-current device and is not seriously affected by slight voltage variations. For the short connections usual in the use of constant-potential arc lamps no special calculation is necessary for the wiring beyond providing ample current-carrying capacity. Series arc lamps take from 4 to 9½ amperes, according to the type. The commonest types are the 4-ampere continuous luminous lamp and the 6.6-ampere alternating or continuous enclosed lamps. The regulation of the Brush generator, of the constant-current transformer, and of the mercury rectifier are all extremely close; it follows, therefore, that the design of the distributing system for exterior illumination will very rarely involve any serious problems of voltage regulation. The series circuits themselves and the resistance in lamps consume a large part of the applied voltage, and the constant-current regulating devices adjust automatically to a wide range of resistance. The series circuits of large cities carry 50, 75 and 100 lamps at voltages from 4000 to 8000. The distance of the separation of lamps varies, but averages from 200 to 300 feet. The voltage drop in the conductor itself is usually between 5 and 10 per cent, and wires in the neighborhood of No. 8 B. & S. are used. The low-tensile strength of smaller wires renders their use inadvisable. It is not uncommon to find a circuit of this kind comprising 10 miles of single No. 8 wire and seventy-five 4-ampere lamps.

Series incandescent lighting from constant-potential high-voltage circuits is accomplished with lamps taking from 1.5 to 4 amperes. For voltages above 550, the circuit should be insulated from the main line by a transformer. In series incandescent circuits fed from constant-current transformers the lamps may be had for currents between 1.75 and 10 amperes. The common size of wire for this class of service is from No. 10 B. & S. up. The regulators are rated in terms of the aggregate kilowatt capacity of total connected lamps. This rating includes an allowance of 5 per cent ohmic and 10 per cent reactive drop in the series circuit.

The insulation of overhead conductors should be of the best rubber core and braided class of manufactured product. The underground conductor may be either fiber-, paper- or rubber-insulated stranded conductor, and in every case is surrounded by lead. These cables should withstand the test prescribed for all

high-voltage apparatus, namely, they should be subjected to double the maximum voltage for a period of 1 minute.

3. *Metering*

The subject of metering is a highly important one in the complete discussion of the entire electric-lighting system. Meters are usually owned, inspected, tested and read by the company supplying power. The illuminating engineer will rarely be called upon to do more than provide proper spacing and accommodation for meters.

Almost invariably the present-day meter measures watt hours. For continuous-current service the best meters are essentially the same as the original Thomson watt-hour meter. This consists of a continuous-current shunt motor containing no iron. The line current flows in the field circuit and the line voltage is applied to the rotating armature with the insertion of a very high resistance. This permanent shunt connection across the circuit, therefore, takes current at all times. While the current of an individual meter is extremely small, nevertheless, the aggregate of the meters of a large system results in quite an appreciable fraction of the total load on the station. The retarding force on the armature of this meter is a copper disc rotating between the poles of several permanent magnets. The shaft of the armature is equipped with a small pinion which engages a train of gears connected with dials constituting the recording mechanism. For alternating currents the induction-watt meter has many advantages over the Thomson type, although the latter may be adapted to alternating-current service. Induction meters operate on the induction-motor principle, series and shunt coils with different phase characteristics, giving the two components of the rotating magnetic field. A light aluminum disc constitutes the rotating element or armature. By their principle they read true power, and are independent of phase difference between current and electromotive force.

Alternating-current meters are, in general, more permanent and reliable than those for continuous currents, in that they have no commutator nor brushes. The present-day meter, as furnished by the best manufacturers, has been brought to a high degree of perfection, and may be relied on to a very close figure of accuracy. No meter, however, will maintain its calibration indefinitely, and those in service should be tested and inspected regularly. This

is generally carried out by the supply company, which in most cases owns the meter. In some instances a meter rental is charged for the purpose of covering not only the original cost of the meter but for defraying this regular charge for inspection and repair. Questions sometimes arise between customers and supply companies as to the accuracy of meter readings, and public service commissions have in many places provided regulations by which a consumer may demand a test and calibration of his meter at any time by the payment of a small fee. The usual method of testing meters is that of comparing them with portable standard meters. It is, of course, necessary that these portable meters should be compared with permanent standard instruments in the laboratory at sufficiently frequent intervals. The methods of charging for power for lighting as based on meter readings will be referred to later in these lectures.

The general subject of meters has been exhaustively covered by the reports of the committee on meters of the National Electric Light Association for 1909 and 1910.

The Installation of Electric Lighting Systems

1. Interior Illumination

(a) **Type of Installation.** The engineering questions arising in connection with the installation of a system of electrical conductors for distributing electric power for lighting are comparatively simple. Such distribution is accomplished at moderate voltages for which the space requirements are not great. The usual problem is that of running a more or less elaborate system of two- or three-wire circuits inside a building. The objects which must be had prominently in view are those of safety, reliability, permanence and unobtrusive appearance. The system must operate without danger of fire or to life. The possibility of fire arises in the results following short-circuits and grounds in the system. The danger to life is not generally present in continuous-current service but arises in alternating-current distributing systems fed from transformers supplied by high-potential primary circuits. It is obvious that satisfactory operation will require that at all times the system will perform its functions of not only distributing power, but in permitting its ready control and the prompt elimination of all abnormal conditions likely to cause interruptions.

The life of the installation depends largely on the materials and quality of labor entering into its construction. In this regard possible exceptions may enter in the installation of systems which are to have intentionally a short existence. Generally speaking, however, the material and workmanship of electric-lighting installations should be of the best obtainable, and in accordance with the latest recommendations of engineering bodies. The distributing system for residences, hotels and dwellings, generally, as well as in all buildings where agreeable and attractive appearance is required, should be as unobtrusive as possible. This consideration in the instances mentioned leads to the entire concealment of electric wiring. In factories and other buildings where no particular attention is required as to appearance, the conductors and supports are often installed exposed. This method is a perfectly satisfactory one, if due attention is paid to the location of the conductors in such places as will render them free from mechanical injury. Exposed wiring presents the general advantage of accessibility and convenience of inspection. Concealed wiring, on the other hand, is almost invariably free from the danger of mechanical injury. Decision as to which general method should be followed will depend on the particular conditions of the problem.

The methods of installing electric wiring are rigidly controlled by the National Board of Fire Underwriters, and the regulations governing this class of work are published by that body in a pamphlet known as "The National Electrical Code." In addition to these rules there is published a list of manufactured material which has been subjected to laboratory test, and which is known briefly as "approved" material. In many cities there is a further list of requirements which apply to particular local conditions.

Four classes of interior wiring are usually permitted. They are known as "open-work," "moulding," "concealed-knob-and-tube" and "metal-conduit" installations. In open work the wires are run entirely exposed and supported on porcelain insulators and knobs; they pass through all walls, joist, partitions, etc., in porcelain tubes. The space requirements in the way of separation of wires from each other, and from walls and their relation to other circuits, etc., are rigidly specified. This type of installation is entirely satisfactory where its appearance can be tolerated, and is the simplest and cheapest to install. The principal precaution

to be taken is against mechanical injury. Moulding and knob and tube work have been developed as methods for installing wiring in buildings originally constructed without any idea of future electric service. They represent the most unreliable and unsatisfactory types of wiring installation. In the case of moulding the wires are run behind either wood or metal strips which are laid on the ceilings and walls of interiors. In knob and tube work the wires are concealed by "fishing" them from point to point behind the plastering and under the floors of buildings without disturbance to these surfaces. This method is highly undesirable, and even when most carefully installed during the progress of building introduces great danger of fire. Both moulding and knob and tube work are make-shifts, and should never be installed by a careful engineer unless absolutely unavoidable.

The complete enclosure of the entire wiring system up to the lamp or fixture outlet in metal conduit represents the best present-day method, and one which bids fair to form the ultimate standard of construction. In this system the entire wiring is completely surrounded by metal. The materials are to be had in the form of rigid or flexible metal conduit. The rigid conduit consists of iron pipe of various sizes, and usually in 10-foot lengths. Elbows, bushings and other fittings are also supplied for each size. This conduit is usually made as soft as possible to permit easy bending for adaptation to building peculiarities. It is either galvanized or covered inside and out with some protective enamel which is valuable in protecting the metal of the conduit rather than as insulation to the conductors enclosed. Flexible conduit comprises the several varieties of the familiar tubing made in spiral form from cut steel. This conduit is best adapted to locations where straight runs are few, and where there is difficulty of access to wiring compartments. With either system of conduit construction iron boxes are used for all classes of outlets. The conduit leads to these boxes and is mechanically and electrically connected to them by means of washers and nuts. These boxes form convenient points for pulling the wires into the conduit after the latter is installed, and also for making connections for branch circuits. This type of installation is readily installed in new buildings, whether they be frame, brick, concrete or other class of construction. Old buildings may generally be equipped with electric wiring in flexible-steel conduit with permanent damage

to plastering only. In the case of concrete buildings the outlet boxes for lamps, switches, plug cut-outs, etc., must be located and firmly attached to the forms with complete conduit interconnection before the concrete is poured. The entire conduit system should form a complete metallic system which should be grounded. In this condition the installation provides practically absolute safety from mechanical injury, and when supplemented by proper cut-outs and fuse apparatus, from fires originating in short-circuits or grounded wires. The only objection to this type of installation which has arisen is the condensation of moisture inside of the conduits. This has been known to take place to such an extent as to result in the rotting of the insulation of the wires due to their permanent immersion in water. This objection may be largely obviated by running the conduit so that there are no pockets in the system, and so that they have a pitch or slope towards some outlet. It is customary to run three-wire mains, feeders and duplex branches in one pipe. It is not permitted, however, to run more than one set in a single pipe. Reliance, therefore, is placed entirely on the insulating covering of the wires without space separation, and on the suppression of any arc or spark between conductors or between conductors and ground by the walls of the conduit. Two-wire service is now limited to the smallest installations, the maximum number of outlets permitted by supply companies on two-wire service varying somewhat, but generally not exceeding 25. It is permissible to run the wires of either two- or three-wire service in a single pipe. The magnetic influence of the iron-protective covering in the case of alternating-current circuits has never arisen as a prohibitive factor. The running of a single wire carrying alternating current in an iron pipe is prohibited by the large increase of the impedance of the circuit and by the heating of the conduit due to hysteresis and eddy currents. A series of tests have been made by the author to determine whether two- and three-wire circuits in an iron pipe could result in any appreciable increase of the impedance of the circuit. Two No. 6 B. & S. wires were separated the maximum distance permitted by the interior diameter of a 1½-inch conduit, being rigidly held in position by strapping to opposite sides of a strip of wood. At 60 cycles, and for currents between 40 and 80 amperes, there was an average increase in the impedance of the circuit over the value when the circuit was in air and not surrounded by conduit of 2½ per cent.

It is obvious, therefore, that in the moderate lengths usually met with in interior illumination, this introduces no disturbing factor.

The lighting of interiors by arc lamps fed from series circuits is to be avoided. As already mentioned, these circuits operate at high voltage, and special precautions must be taken in insulating any such circuit within a building. In most localities the introduction of such circuits into buildings is prohibited.

Multiple-connected arc lamps are frequently used for the lighting of stores, factories, sheds, etc., and they are supplied by low-voltage distributing mains. In such circumstances due consideration must be given to the regulation of these circuits if incandescent lamps are also to be operated from them. The arc lamp takes from 4 to 9 amperes, and when this is the only type of lamp on the circuit the carrying capacity is often the determining factor rather than any question of regulation. The National Electrical Code prescribes the maximum values of current which it is permitted to carry on various sizes of wire. Each lamp or series of lamps, in case several are operated in series, must be provided with a fused cut-out. The general description and rules covering incandescent wiring, as already described, apply also to multiple arc circuits, but the underwriters' requirements prescribe certain additional regulations, which are duly set forth in the publications mentioned above.

(b) **Control.** It is obvious that the entire system of an interior installation should be under control. We may define "control" as the possibility of individual and separate operation of all lamps, and the prompt cutting out of any portion of the system which may develop trouble. Thus every lamp or group of lamps should be operated by an accessible switch, and every branch circuit should also be equipped with apparatus permitting its easy separation from the remainder of the system. Individual distributing centers or the feeders supplying them should be equipped with switches. In addition to these essentials for manual operation, the whole system must be protected by fuses or automatic circuit-interrupting devices. It is highly essential that the main distributing center, the service connections, and all subsidiary centers should be in well-illuminated and readily accessible locations.

In the denser sections of a distributing system, the service wires will usually be brought in from underground. Connection to a residence is usually made from a manhole permitting access to

the underground network. The manhole is an essential part of a system of underground ducts. The building connection is usually made from these manholes by small conduit connection, this conduit being made either of fiber, treated wood, terra cotta or any of the many types offered by the market. These conduits are brought through the building line underground, and the service wires brought above the surface by a continuation of the conduit or in iron pipe. These conduits should drain back to the manhole, that is, away from the house, and after the wires are drawn in the conduit opening should be stopped so as to prevent gases from flowing into the building.

In the outlying districts where the distribution is overhead various methods are used for bringing the service wires inside buildings. In many instances this is done by putting suitable bushings through the walls near the roof of the house. The best practice, however, takes the service wires from the transformer into an iron pipe some distance above ground level, the pipe leading below ground into the basement as already described. This pipe connection should be provided at the top with a rain-proof bushing, and is particularly desirable in localities where there is a possibility of future underground service. The report of the committee on overhead construction of the National Electric Light Association, 1910, describes in detail various methods of making service connections.

Interior-lighting systems, whether supplied from isolated plants or from public-service companies, should be equipped with a main switch controlling the entire system. Also each feeder should be equipped with a switch. The next subdivision at the distributing centers should provide either a switch or enclosed fuse for each two-wire branch. The main switch of the system, and the individual feeder switches, should each be equipped with fuses or supplemented by some form of automatic circuit-interrupting device. It is sometimes desirable to have a switch at the distributing center, although this is not necessary if the feeder furnishing this center is so equipped. Branch circuits must be equipped with fuses, but not necessarily with switches. The underwriters' requirements limit the capacity of a single circuit from a distributing center to 660 watts. This figure was probably originally based on the demand of twelve 55-watt carbon lamps. And, in general, branch circuits in the past have been limited to 10 or 12 outlets.

It is now possible to run many more outlets to a branch circuit by the use of low-power tungsten lamps. The branch circuits for incandescent lighting are usually protected by fuses of 10-ampere capacity. These fuses are either of Edison "screw-plug" or of "cartridge" type, with present tendency to a return to the former. As already stated, the feeders must be protected by fuses, and for this purpose the "cartridge" fuse is best. In many large installations the feeders are protected by circuit breakers located on switchboards of more or less elaborate design. The requirements of theaters lead to especially detailed switching and regulating devices. Fuses are manufactured up to 500- and 600-ampere capacity, but circuit breakers are preferable above the former figure on account of the cost of the fuses and of the time required for their operation. Flexible cable must be used in all conduit installations, and may be had to accommodate practically any current. In the larger installations feeders frequently have a cross-section of 500,000 circular mils, and in extreme instances are even of greater size. The subdivision in these cases of the total capacity required is highly advisable on the score of convenience of installation. The installation of conduit of diameter larger than 2 inches will usually involve difficulties unless special provision is made in the design of the building. Two-inch conduit will accommodate three No. 00 wires; 3- and 4-inch conduit has been used, but 2 inches marks the limit for convenient installation. The neutral wire is made of full size in all interior wiring, so that when for any reason one side of the circuit is interrupted the neutral will provide full carrying capacity for the return current.

(c) **Cost of Interior Wiring.** Since the prices of labor and material differ in different localities and at different times, it is difficult to state even approximately what the cost of distributing systems for lighting should be. In large cities, however, these variations are not very wide, and it is possible to state the limits within which the cost, expressed in terms of the usual contractor's price per outlet, should lie. The figures given below apply to interior wiring of all classes, from the small residence up to the large hotel or office building. They cover the portion of the work from the main source of supply, assumed to be at the building line. In case the building is lighted from its own plant these figures will apply to the portion of the installation lying between

the lamp and the plant switchboard. No lamps, fixtures or reflectors are included in these prices:

Exposed wiring, \$1.50 to \$1.60 per outlet.

Wire in wooden moulding, \$2.00 to \$2.50 per outlet.

Concealed knob and tube wiring, \$2.50 to \$3.00 per outlet, with \$1.00 added per switch outlet.

Wiring in iron conduit and in new buildings, \$4.50 to \$5.00 per outlet.

Wiring in iron conduits in concrete buildings, \$5.00 to \$6.00 per outlet.

In the above, switches and base-board plugs are considered as outlets when the iron box is included. If the switch and plate is also to be furnished, approximately \$1.00 per outlet of this nature should be added. For the larger installations in modern buildings the price of \$7.00 per outlet, including all wiring and feeders up to the lighting fixture, has been found to be a fairly close figure.

For that portion of the wiring which may be necessary beyond the building line, as, for instance, the service connection and transformers, in those regions where alternating service is supplied, it is hardly possible to state even approximate figures of what the prices will be. The cost of wire follows that of copper more or less closely, and transformers vary somewhat in price. Lighting transformers suitable for erection on poles and for 60-cycle operation may be had in any capacity between 6/10 kw. and 50 kw. As adapted to 1100 or 2200 primary circuits, and transforming to 110 or 220 two- or three-wire secondary, their price varies from \$27.00 per kilowatt for the 1-kw. size to between \$7.00 and \$8.00 per kilowatt for sizes in the neighborhood of 40 kw. and 50 kw. The prices are somewhat higher for higher primary voltages, and transformers adapted to location in subways are from 10 to 12 per cent more expensive than the usual out-of-door type. Transformers for 25 cycles cost from 40 to 50 per cent more than those for 60 cycles.

(d) **Fire and Insurance Control.** The National Board of Fire Underwriters, and in most places municipal regulations, require strict supervision of the installation of electric wiring. It is usually required that the electrical contractor shall secure a permit for any new work or repairs to electric wiring in buildings. In many cases the fire underwriters are satisfied with the municipal super-

vision and make no independent demands of their own. This is especially the case where the city adopts the National Electrical Code for its own regulations. Presumably this permit for wiring is followed up by an inspection of the work after completion, by a city official. Too often, however, this inspection is of the most perfunctory character. The inspector will almost invariably be content with a visual inspection of the installation. From the nature of the troubles and imperfections that are likely to arise from a system of wiring, electrical tests are the only ones which can yield complete evidence as to the state and the character of the work. Insurance and city authorities therefore would do well to require a thorough testing of every installation before approval and acceptance. Since there is at present no municipal regulation which ensures tests of this nature, the designing engineer should be careful to incorporate in his specification clauses requiring the complete testing by the contractor. This method of accomplishing the testing should be easily available to the city, which in yielding a permit could stipulate that before acceptance proper tests should be made in the presence of the city official.

It has been already mentioned that the entire system of metal conduit of an interior installation should be grounded. Grounding means connecting as definitely and permanently as possible to the earth, thus maintaining the grounded portion at the potential of the earth. The neutral of underground direct-current systems is almost invariably grounded. Interior-wiring systems should, in the writer's opinion, be always grounded. Ground connections may be readily made by connecting between the grounding point of the circuit and the metal pipes of the city water supply. Such connections should be soldered and of fairly large size of wire. To ensure a ground independent of water or gas pipes an iron pipe may be driven 5 or 6 feet into solid soil, the damper the soil the better, and the ground connection soldered to this pipe. The conditions will be improved by using several pipes and by removing the earth from around the top of the pipe to a depth and diameter of about 1 foot each, and then filling this hole with salt.

There has been a wide discussion as to the advisability of grounding alternating-current secondary circuits. These circuits are usually three-wire, and the ground connection should obviously be taken from the neutral. The great advantage of grounding the neutral is in the fact that should the primary voltage reach the

secondary wiring by the failure of a transformer or by the crossing of the respective lines, the high-voltage circuit thus brought into connection with the low-voltage wiring would be grounded and thus prevent arcing and danger to life. In many instances, also, electrostatic charges may be induced in the secondary wiring by disturbances in the primary circuit. This may result in serious shock to persons handling the secondary circuits if these circuits are not grounded.

The supposed objection to grounding such circuits is that it places the potential of one side of the three-wire system between the bare contacts on lamps and other devices and the ground, thus offering the possibility that persons receive shocks. The National Electric Light Association recommends that the grounding of secondary circuits be limited to those on which the voltage of one side does not exceed 150. This means that no shock of a higher value than that stated could be received by anyone touching an uninsulated portion of the circuit. The reasons for not grounding circuits of higher potential do not appear to be good. There can be no question that the grounding of the circuit offers great protection from any trouble that may arise from the primary circuit. This is undoubtedly the most likely and the most serious source from which trouble may come. The danger of shock to persons is hardly greater when the system is grounded than when it is not, and in those systems in which the voltage is carried to values dangerous to life it would appear desirable to provide the safeguards in other ways, such as complete insulation of all live contacts, or by other methods usual in high-voltage circuits.

(e) **Specifications and Contracts.** In preparing specifications and making contracts for an installation it is highly desirable that each should be as complete and explicit as it is possible to make them. The specifications should always be accompanied by drawings. Of the numerous clauses for the protection of the client which should be inserted, none perhaps is more important than that applying to the charges for alterations or extensions of the work, as set down in the specification. In competitive bidding on work of this nature a contractor will often look to his charges for extras and alterations for the best part of his profit. The engineer should therefore endeavor to describe on the drawings or by explicit statement every outlet of installation. General clauses should be inserted which shall protect the client during the process

of the work from damage to persons and property, and relieve him from all responsibility until the installation is ready to be turned over complete. In large installations the contractor should be required to place insurance on completed portions of the work and to give bond for its completion within the date stipulated in the contract. The specifications should cover carefully the sizes of all mains, feeders and branches, together with the conduit in which they are placed. Full details should be given of all switches, distributing boards, panels, etc. The trade names of manufactured articles which will be accepted should also be given, and the general statement made that no material not approved by the Board of Fire Underwriters may be used. The drawings should show the accurate location of all outlets, service connections, distributing centers and the run of all feeders. It is highly desirable that the engineer and architect should have early consultation so that the latter may know what space will be required by the engineer. Too often the architect's plans are completed before the engineer sees them. The architect, as a general thing, has a very limited knowledge of the requirements of an electric-wiring installation, and it is usually assumed that the illuminating engineer requires no space at all for his circuits. This consultation is especially advisable for buildings of reinforced concrete where it is inadvisable to pass conduit through reinforced beams.

The drawings should also indicate the type of fixture, lamp, reflector, mounting height, etc. The National Electrical Contractors' Association has published a set of symbols which are in general use for indicating the nature and location of distributing centers and the various types of outlet, etc. A standard set of symbols of this nature applying to the different methods of mounting lighting units and describing their character would be very useful.

The wiring for lighting systems is often installed on what is known as the time and material basis. This means that the contractor charges the cost of material used and the hours of labor required to the owner, with a certain percentage added. This is rarely, if ever, a satisfactory method to the owner. To ensure a reasonable charge it requires a constant inspection of material and labor time. It will usually be possible to secure competitive bids, and then require the contractor to give the owner the benefit of any saving under the contracted figure which results from keeping

a record on the time and material basis. In such a case the contractor furnishes the engineer with a statement of material and labor time at regular intervals.

(f) **Tests.** Satisfactory performance in wiring installations depends primarily on regulation and on the nature of the material and workmanship. The regulation will depend largely on the sizes of conductor specified by the engineer, and a test of regulation will only check up the methods which have been employed in making joints and contacts. A full-load test, however, should be invariably applied to the system before its acceptance. Every switch should be operated and each lamp socket and base-board plug tested. Insulation tests are rarely applied to interior-wiring systems. It is advisable, however, to apply at least double the normal operating voltage to the completed system. A stipulation to this effect should be included in the specification. The contract should contain a clause requiring the contractor to carry out the tests in the presence of the engineer and the details of this test should be given.

2. *Exterior Illumination*

(a) The commonest form of outside-lighting circuit is that of the series incandescent or arc system. These circuits are usually run overhead, except in the more densely populated portions of the city. No special comment, therefore, seems needed as to the installation beyond the regulations set down by the National Electrical Code. These circuits are of moderate voltage (from 2000 to 8000), and may therefore be handled by a variety of approved grades of manufactured wire, insulators, etc. Series circuits are controlled, as a whole, from a generating station or substation, the entire protective apparatus being installed there. Special precautions may be necessary in some places for the protection of low-voltage lighting circuits and of telephone and telegraph wires. This class of service is more satisfactory when run in underground conduits, and this is usually required by the authorities in the centers of large cities. The cities usually own the conduit system and rent space to the supply companies. The single conductor of the arc or incandescent circuit is insulated with rubber or paper and the whole covered with lead. The manholes of the duct system are usually from 400 to 600 feet apart, and individual lamps are fed through branch conduits between the manhole and the base of the

pole. The cables then rise inside the iron pole to the lamp. Since there is little or no difference in potential between the two sides of such a loop from a manhole to a lamp, a duplex conductor may safely be used for this portion of the circuit. The lamp itself, however, should be insulated from its support, since it may receive the full potential of the circuit. Grounds on this class of circuit are very dangerous. The lead sheathing of underground cables usually affords sufficient protection between mains of different classes of service; thus arc circuits are frequently run in the same duct with the low-potential multiple-distribution mains. Instances have been known in which trouble has arisen by reason of this proximity, but a rental charge on the part of a city of 5 cents per duct foot per annum is usually sufficient to cause the supply company to put as many conductors as possible in one duct. Excellent data as to the construction of conduits, their cost, etc., may be found in the Standard Hand-Book for Electrical Engineers.

3. Cost of Operation

There is probably no phase of the general problem of electric lighting which attracts more public discussion than that of its cost. Public-service corporations, particularly if they have a monopoly of the consuming market, are naturally the objects of public suspicion. This is especially true of companies selling electricity for lighting, and the explanation is to be found in the great discrepancy always existing between the admitted cost of electrical energy at the station bus-bars and the price at which it is sold to the consumer. The latter figure is often ten or more times as great as the former, and consequently is often the object of uninformed public clamor. The reasons for the difference will be better understood after a discussion of some of the factors entering into the actual cost of generating and delivering electric power.

(a) **Cost of Electric Power.** The commonest basis of estimating the cost of electric power is the summation of all expenditure necessary to deliver the power at the station feeder bus-bars ready for distribution. This total cost divided by the total energy generated gives the unit cost, i. e., the cost per kilowatt hour. This apparently simple method, however, will rarely yield the same figure for two different months, or weeks, or even days in the year, for the total cost of electric power is not directly proportional to the amount generated.

The total cost may be divided into two classes: (1) *fixed charges* and (2) *operating expenses.* In the item *fixed charges* are included all expenditures necessary whether or not the plant generates power. Thus in this class fall the items of interest, taxes, insurance, depreciation and obsolescence. They represent the aggregate cost of having an up-to-date power station ready to deliver power. By depreciation is meant the outlay necessary to keep all generating equipment in repair, and to replace efficient apparatus worn out in service. By obsolescence is meant the cost of purchasing apparatus and equipment to replace that which has been rendered obsolete and inefficient by improvements and increased knowledge of the art. Interest and taxes expressed in per cent of the cost of the plant will not vary with the type of plant; insurance is often eliminated entirely in modern plants of fire-proof construction; depreciation and obsolescence vary widely with the type and size of plant, being greatest for reciprocating steam plants and least for water-power plants. The aggregate of fixed charges, in per cent of the cost of the plant, varies from 9 to 17 per cent in modern plants of size required to furnish city lighting service. The lower figure is reached only in the best type of water-power plant, and the upper refers to reciprocating steam engines operating under poor conditions. The cost of the power plant varies from $80 per kilowatt of installed capacity, in the case of steam turbines, to $100 or $125 for reciprocating steam engines, and to $200 or more for water-power plants. Large gas-engine plants cost about $135 per kilowatt of installed capacity.

The second class of expense in the production of power is called the *operating expense,* and it includes all items, such as fuel, oil, attendance, etc., which are approximately proportional to the amount of power generated. The proportionality between total operating expenses and amount of power generated is not exact, since the efficiency of steam and electrical apparatus is not the same for all values of the load upon them. With proper subdivision of the total capacity into smaller units, however, it is usually possible to operate with machines loaded to more than 50 per cent of their rated capacity, and in such conditions the operating expenses per kilowatt hour are approximately uniform at all times. Average values of operating expenses in large stations are .3 cent per kilowatt hour for gas-engine plants, .4 to .5 cent for steam-turbine, and .6 cent for reciprocating-engine plants.

It is obvious that since the fixed charges are constant and the operating expenses proportional to the amount of power generated, the cost per kilowatt hour will be least when the station is generating its greatest output. The minimum possible cost would be reached if the station could operate continuously at its maximum capacity. In such a case, at 12 per cent fixed charges, an up-to-date steam-turbine plant could generate power at the feeder terminals at approximately .5 cent per kilowatt hour. Unfortunately, however, the maximum load on the usual central station lasts a very short time, the load curve having a sharp peak in the late afternoon and early evening hours. The value of the maximum power output shown by this peak determines the capacity required at the central station. Consequently, at periods of light load, as for instance, during the morning hours, fixed charges must be paid on more generating equipment than are required to handle the load. This variation of the load throughout the day, in its effect on the cost of power, is described in terms of a quantity known as the "load factor," which is the ratio of the average daily, monthly or yearly load to the maximum loads occurring in the corresponding intervals. The daily load factor then is a quantity less than 1, and represents the proportion of the maximum daily power output which may be multiplied by 24 in order to arrive at the total number of kilowatt hours generated through the day. It is therefore highly desirable to increase the average daily load, and so render the load factor as near to the value 1 as possible. The load factor corresponding to lighting service only is very low, and lighting companies make great efforts to develop a day load comprising motors of all kinds, and heating, cooking and other domestic appliances. The daily load factor of a large central station, which supplements its lighting load in every way possible, is about .50; the yearly load factor about .30. At load factor .50 the average total cost of generation in a gas-engine plant is .65 cent, in a steam-turbine plant .7 cent, and in a steam-engine plant about .9 cent per kilowatt hour.

(b) **Systems of Rates for Sale of Power.** In the early days of electric lighting it was customary to charge a consumer simply in terms of the number of lamps installed without reference to the number of hours they were used. This method of charging, known as the *flat-rate* system, was obviously unfair to the economical user, and meters for reading the total number of kilowatt hours were

developed as a basis for charging. This method alone, however, is obviously not equitable, since it costs the supply company more to supply a consumer during the time of peak load than at other times. Consequently, consumers are often classified on some basis representing the times of the day during which they take their maximum power, and different rates apply to the several classes. Such a classification might separate, for instance, the services to residences, to stores or factories, and to day motors. A further refinement in the methods of charging is found in the so-called *two-rate systems,* which aim to charge a consumer a higher rate for the power he uses during his peak hours and a lower rate for the remainder. This method evidently aims to charge each consumer his proportionate share of the fixed and operating charges, respectively. The obvious difficulty is that of ascertaining the maximum load of each consumer. For residence lighting it is usually assumed that some proportion of the total number of lamps connected will be burned together for a definite number of hours each day. This number of kilowatt hours will then be charged for at the higher rate, and all power in excess at some lower rate. *Maximum-demand* meters, which indicate the highest value of power taken during any chosen interval, have also been used as a means of arriving at the value of a consumer's peak. This, however, constitutes a separate measuring instrument for each consumer, and on account of the expense involved the plan has not as yet been widely adopted.

The actual price at which power for lighting is sold varies widely in different places. In the larger cities the primary rate is rarely less than 10 cents per kilowatt hour, which may be charged, for instance, for all power up to the amount consumed by one-half the connected load if burned for 30 hours. All power in excess of this during the month would then be charged for at a less rate, say 7 or 5 cents per kilowatt hour. One reading per month of a meter indicating kilowatt hours, therefore, serves to fix the amount of the consumer's bill.

The wide discrepancy between the prices at which power is sold and the cost of its generation have led to frequent agitation by the public of the question of regulating the rates for the sale of power by law. This type of discussion arising as well in connection with other classes of public-service corporations has led to the formation in many states of public-utilities commissions, which have

the power to investigate and regulate the conditions of manufacture and sale of the respective public commodities. The figures of cost of generating power which have been given apply at the station bus-bars. The discrepancy alluded to above includes the cost to the supply company of distributing the power to the consumers, the cost of meters and their regular inspection, and the general office expenses. While the cost of distribution, which includes the capital charges on all the distributing system, as well as its inspection and maintenance, duct rentals, etc., is usually a much larger figure than at first apparent, the several items mentioned do not bring the actual cost of delivering the power to the consumer very near to the figure at which it is sold. The remaining difference is not all profit to the company, however, but is in part applied to paying the obligations of early lighting companies, bought up by the present one, and defunct through obsolescence or other cause. It is worth noting that a recent careful investigation by a public-utilities commission of the rates charged by a lighting company in a large city in the middle West resulted in a decision that 14 cents and 8 cents per kilowatt hour were equitable primary and secondary rates.

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VII (1)

PRINCIPLES OF MANUFACTURE AND DISTRIBUTION OF GAS, WITH PARTICULAR REFERENCE TO LIGHTING

By E. G. Cowdery

CONTENTS

Manufacturing.
- General characteristics of coal gas and water gas.
- Effect of different constituents on the calorific value and illuminating power of coal gas.
- Illuminants, their characteristics.

Manufacture of coal gas.
- Open furnace heating of benches.
- Regenerative furnace heating of benches.
- Development in the retort under varying heats and conditions.
- Brief references to through retorts.
- Brief reference to vertical retorts.
- Brief reference to inclined retorts.
- Brief reference to by-product coke oven process.
- Purification of coal gas.
    - Tar extraction.
    - Cooling.
    - Ammonia extraction.
    - Sulphur extraction.

Carburetted water gas.
- General statements.
- As made from fixed carbon, steam and oil.
- Development.
    - Harris process.
    - Tessie du Motay.
    - Lowe process.
    - Treatment of different oils.
        - Paraffin base oil.
        - Semi-paraffin base oil.
        - Asphalt base oil.
    - Basic claim Lowe patent.
    - Efficiency of Lowe apparatus.
- Purification of water gas.

Carburetted water gas made from oil and steam only.

Producer gas.

Metering gas at the manufacturing station.

Gas holders.

Distribution.
- **Low pressure.**
- **District holders.**
- **Reinforcing pressure mains.**
- **High pressure for suburban or long distance distribution.**
- **Semi-high pressure or "Booster" system.**
- **Formula for flow of gas through pipes.**
  - **Low pressure.**
  - **High pressure.**
  - **Excessively high pressure.**
- **Location of gas works.**
- **Station governors.**
- **Design of a distribution system.**
- **Drainage of mains.**
- **Pipe joints.**
- **Brief mention: services, gas meters, house piping and photometry.**
- **Calorimetry.**

There are three characteristic ways in which manufactured gas is used, each of which, in its own sphere, results in its extensive employment as an agent for the production of artificial light. When burned without previous mixture with air, it produces a flame of considerable intrinsic brilliancy; when burned after previous mixture with air, it produces a non-luminous flame of high temperature; and, thirdly, the application of its explosive action, when mixed with air and ignited in the cylinders of gas engines, places certain grades of artificial gas among the most economical agents for the production of power.

I shall devote myself mainly to a description of the principles involved in the manufacture and distribution of the various gases delivered by the artificial-gas companies of the United States, but attention is purposely called to the use of producer gas for the production of power, as being an important modern means towards conservation of energy, and this phase of the subject will be briefly presented.

Kinds of Gases. The gases we will consider are generally classified as follows:

Illuminating gas is divided into two great classes, coal gas and carburetted water gas.

Coal gas in turn is divided into two sub-classes, viz., that produced by the distillation of gas coal in comparatively small retorts, and that produced by the distillation of coking coal in larger ovens.

Carburetted water gas, on the other hand, is divided into that made from fixed carbon, steam and oil, and that made from oil and steam only.

Producer gas is made by the action of steam or air, or both, upon fixed carbon.

General Considerations. From this classification it becomes evident that coal gas is produced analytically, distilled from certain kinds of coal, while water gas and producer gas are synthetically made, that is, built up from the action of several constituents upon each other in a manner to be described later.

The results in each case do not widely differ, as is illustrated in the table shown as Slide 1. In this connection it is to be understood that the analyses shown are representative only, and not absolute, under all conditions.

Producer gas has been omitted from this table, but will be considered later on.

It is to be noted that the use of water gas made from steam and oil, owing to local conditions of supply of the raw materials, is at the present time practically confined to the Pacific slope, where it is extensively used. It is particularly interesting to note how closely this gas compares in composition with coal gas, although produced from very different materials.

In this country, generally, and in Europe and Great Britain, carburetted water gas is understood to be the gas produced from coal or coke, steam and hydrocarbon oils, as shown in the third column of the table.

TABLE OF GENERAL CHARACTERISTICS OF COAL AND WATER GAS

	Coal gas made in		Water gas made from				
Per cent by volume.	Retorts.	Coke ovens.	Steam fixed C. and oil.	Steam and oil.	B. t. u. per cu. ft. 60° F.	Spec. grav. at 60° F.	Candle-power per 5 cu. ft. per hour.
Illuminants	4.75	4.8	12.8	7.01	2235.	1.4	0
Ethane	36.02	36.0	2.8		1764.4	1.0368	38.7
Methane			13.4	34.64	1009.	0.5529	5.2
Hydrogen	47.04	49.7	33.9	39.78	326.2	0.0692	0
Carbon monoxide	8.04	4.1	30.9	9.21	323.5	0.9671	0
Carbon dioxide	1.60	1.3	2.8	2.62	0	1.5195	0
Oxygen	0.39	0.7	0.6	0.16	0	1.1052	0
Nitrogen	2.16	3.4	2.8	6.58	0	0.9701	0
Total	100.00	100.0	100.0	100.00			

	Coal gas made in		Water gas made from	
	Retorts.	Coke ovens.	Steam fixed C. and oil.	Steam and oil.
Specific gravity	.426	.391	.683	.482
B. t. u........................	678.	675.	682.	680.
Candle-power	16.0	15.8	22.	19.69
Cu. ft. air req'd for combustion one cubic foot..............	5.65	5.63	5.74	5.81

NOTE.—The B. t. u. per cubic foot of "illuminants" varies considerably in different gases. In computing the amount of air required for combustion the illuminants were assumed to have a composite formula of C_2H_4.

In discussing this table it is to be noted that each gas differs from the other only in the relative proportion of the same constituents. To indicate this more clearly, it is seen that coal gas contains less illuminants, usually more hydrogen, considerably less carbon monoxide, and less carbon dioxide than water gas.

These characteristic features exercise a considerable effect upon the candle-power, calorific value and specific gravity of the gases. For instance, a smaller amount of illuminants means lower candle-power, usually lower heat value and higher specific gravity. More methane means lower candle-power, usually higher calorific value, but it is of lesser specific gravity than the illuminants.

An increased quantity of hydrogen means lower candle-power, lower heating value and very much lower specific gravity.

Carbon monoxide burns with a blue flame, and in itself has only a relatively low calorific value. Carbon dioxide, being the product of the combustion of carbon, when present in gas, decreases the candle-power and heating value, but increases the specific gravity.

These comparisons are general only, and give the result of the effect of any one of these constituent gases, considered from the point of view of such gas only, without consideration of the effect of other constituents at the same time. For instance, it might conceivably happen that an increase in the proportion of methane would be accompanied by such a large decrease in the percentage of carbon dioxide and nitrogen that the candle-power might actually be raised. In other words, it is necessary to look at the composition of a gas as a whole, in order to arrive at a satisfactory idea of the various enumerated properties.

Dr. William B. Davidson, of Birmingham, England, in his recent paper entitled, "Experiments in Carbonization on the Bir-

mingham Coal-Test Plant," read before the British Institution of Gas Engineers in 1910, gives some interesting data on the effect of these various constituents on coal gas. An extract from the same appears as follows:

"In this connection it is interesting to consider the effect of each of the main constituents of coal gas on both the illuminating power and the calorific value. On this subject, the information available in technical literature is both incomplete and incorrect, and I have therefore undertaken a series of laboratory experiments with the object of ascertaining the effect on candle-power of admixtures of small quantities of different gaseous constituents.

The effect on calorific value is already known. The approximate results are given in the following table, and apply alike to No. 2 and No. 1 argand burners used with full flame.

EFFECT OF DIFFERENT CONSTITUENTS ON THE CALORIFIC VALUE AND ILLUMINATING POWER OF COAL GAS ON A BASIS OF 540 B. T. U. AND 16 CANDLES.

Constituents.	Calorific Value Per Cent.	Illuminating Power Per Cent.	Ratio.
CO_2	—1.0	—3.5	1 to 3.5 decrease
O	—1.0	—3.0	1 to 3.0 "
N	—1.0	—2.6	1 to 2.6 "
Air	—1.0	—2.7	1 to 2.7 "
CO	—0.4	—0.5	1 to 1.0 "
H	—0.4	—0.5	1 to 1.0 "
CH_4	+0.9	—0.6	Increase in calorific value = twice the decrease in illuminating power.
C_2H_4	+1.9	+10.9	1 to 6.0 increase
C_6H_6	+6.0	+18.0	1 to 3.0 "
$C_{10}H_8$	+10.5	+125	1 to 12 "

NOTE.—Gas *saturated* with naphthalene vapor at 60° F. contains only 0.0085 per cent by volume of this constituent. The increase in candle-power, due to this small amount, is only 0.16 or 1 per cent. It should be understood the per cent of illuminating power given is theoretical and true only within narrow limits.

The figures for carbon dioxide, oxygen and nitrogen have been confirmed by experiments with the large test plant. It calls for remark, however, that in short trials the effect of the admission of air was not nearly so drastic as was indicated by laboratory tests. This was doubtless due mainly to the fact that the iron oxide underwent a large rise in temperature and threw off certain

hydrocarbons—chiefly benzene—with which the water in the material had become saturated. In one instance, the admission of 3 per cent of air appeared to effect no reduction at all on the multiple. In experimenting with air it is, therefore, necessary to allow the plant to attain equilibrium before starting the test, and to prolong the trial.

It will be observed that the effect of an admixture of 1 per cent of nitrogen reduces the candle-power by about 2.6 per cent. As it is this ingredient that varies most of all in the composition of coal gas as manufactured in this country, and seeing that the effects of carbon dioxide, oxygen, carbon monoxide and benzene have all nearly the same ratio, it follows from theoretical considerations that 2 per cent reduction of illuminating power for 1 per cent reduction of calorific value the result previously indicated is approximately what we should expect to find."

For purposes of gas-engine use a gas should be able to withstand a relatively high compression without undue loss or premature explosion. Methane withstands high compression without change.

However, it may be stated that in general, for illuminating gas, the illuminants, ethane, methane, hydrogen and carbon monoxide are all desirable constituents, because they all add candle-power or heating value, but carbon dioxide, oxygen and nitrogen are undesirable because of the lack of these properties.

Illuminants. The illuminants play a large part in the characteristics of candle-power and calorific value of both coal and water gas. Some of the more important of these compounds, with their special characteristics, are given in the following table:

TABLE OF ILLUMINANTS

Series	Name	Chem. Formula	Spec. Grav. Gas or Vapor Air=1	Illum. Value per 5 cu. ft. per hr.	B. T. U. per Cu. Ft.	Cu. Ft. Air Req. for Comb. of 1 Cu. Ft.
C_nH_{2n}	Ethylene	C_2H_4	0.9676	68.5	1588.0	14.355
"	Propylene	C_3H_6	1.4514	....	2347.2	21.533
"	Butylene	C_4H_8	1.9353	123.	3099.2	28.710
"	Amylene	C_5H_{10}	2.4191	....	3847.2	35.888
C_nH_n	Acetylene	C_2H_2	0.8984	240.	1476.7	11.963
C_nH_{2n-2}	Allylene	C_3H_4	1.3823	....	2227.1	19.140
"	Crotonylene	C_4H_6	1.8661	....	2975.6	26.318
C_nH_{2n-6}	Benzene	C_6H_6	2.6953	349.	3807.5	35.888
"	Toluene	C_7H_8	3.1792	....	4552.0	43.065
"	Xylene	C_8H_{10}	3.6630	....	5294.2	50.243
"	Mesitylene	C_9H_{12}	4.1468	....	6108.0	57.420
C_nH_{2n-12}	Naphthalene	$C_{10}H_8$	4.4230	930.	5906.8	57.420

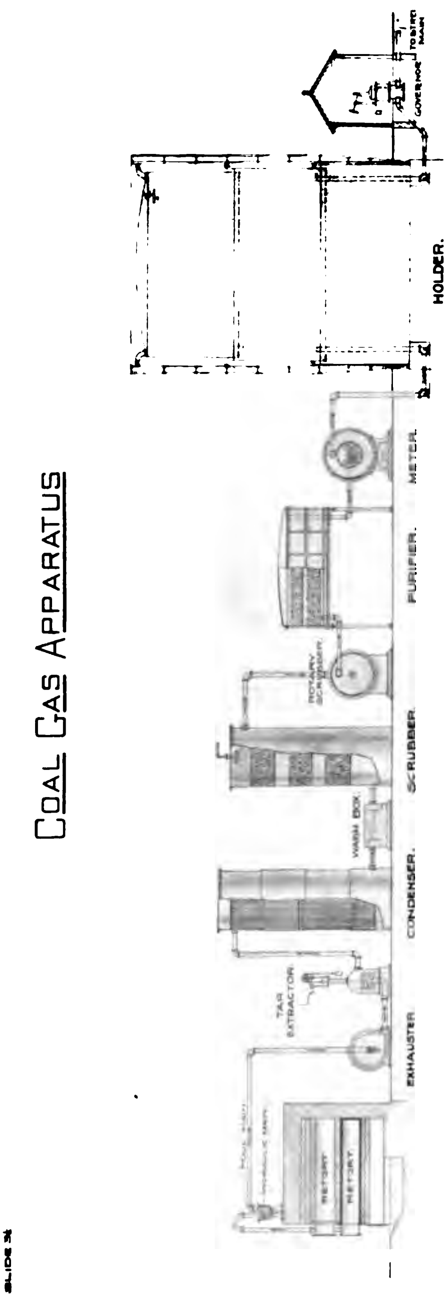

COAL GAS APPARATUS
RETORT.
RETORT.
EXHAUSTER
TAR EXTRACTOR
CONDENSER.
WASH BOX.
SCRUBBER.
ROTARY SCRUBBER.
PURIFIER.
METER.
HOLDER.
GOVERNOR
TO STREET MAIN

FIG. 1.

NOTE.—All volumes of gases and vapors are given at 60° F. and 30″ pressure. Benzene, being a liquid under ordinary conditions, was tested for candle-power by mixing its vapor with hydrogen, and a slit burner used.

Naphthalene, being ordinarily a solid, was similarly mixed with coal gas.

Coal-Gas Manufacture—As Produced in Retorts

The art of coal-gas manufacture is over a century old. William Murdoch, in England, between the years 1792 and 1798, was engaged in experimenting with different coals, and in devising apparatus for their distillation. In 1797-1798 lighting by coal gas was actually accomplished, for Murdoch, by means of his experimental plant, first lighted up his dwelling house, and a short time later a much larger building at Birmingham.

From these first attempts, coal-gas manufacture has been developed to the present state of the art.

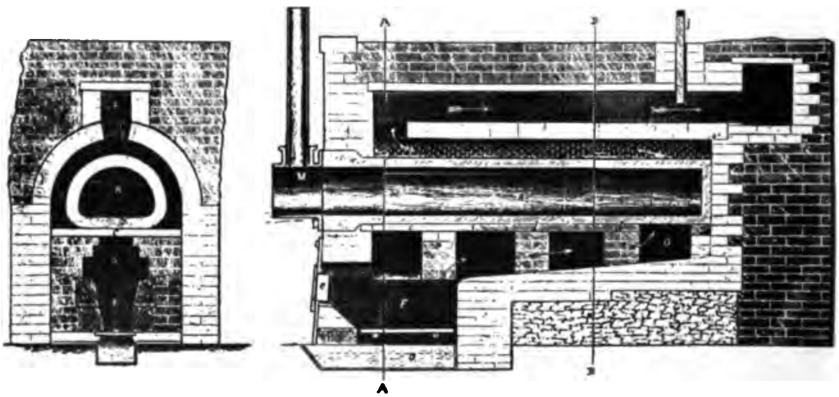


FIG. 2.—Simple Retort Setting.

Principles of Coal-Gas Manufacture

The generation of coal gas from gas coal is a process of destructive distillation. The solid coal is charged into the retort, which in laboratory parlance would be called a muffle, and the retort is heated externally.

Figure 2 shows a setting, which, though too primitive for modern use, exemplifies the primary principles. It consists of a retort set upon parallel fire-brick piers having openings through them for the passage of the heated products from the furnace, a furnace for heating, an open space around the retort to per-

mit its envelopment by the heated products of the fire, and a flue for the escape of the products. The retort of burnt fire-clay, 3 inches thick, cross-section oval, D shape or circular, being open at the front end only, has bolted to that end a cast-iron extension called a mouthpiece, which, projecting from the front wall of the setting, is fitted with a gas-tight door, through which opening the coal is introduced and the coke withdrawn. At the top or side of the mouthpiece is an opening to which is connected a cast-iron pipe rising vertically, the upper end dipping into a seal of water. When the charge of coal is placed into the heated retort distillation immediately begins, vapor and gases, air and steam being given off until the pressure is sufficient to overcome the seal in the dip-pipe, when the gas begins to bubble through and continues until carbonization (by which is meant destructive distillation of the coal) ceases. The door is then opened for the withdrawal of the coke remaining in the retort and reintroduction of fresh coal. As soon as the door is opened there is a return of pressure in the retort to normal atmospheric, the water rises in the dip-pipe thereby preventing gas, from the collecting main from all the retorts, escaping through the open door.

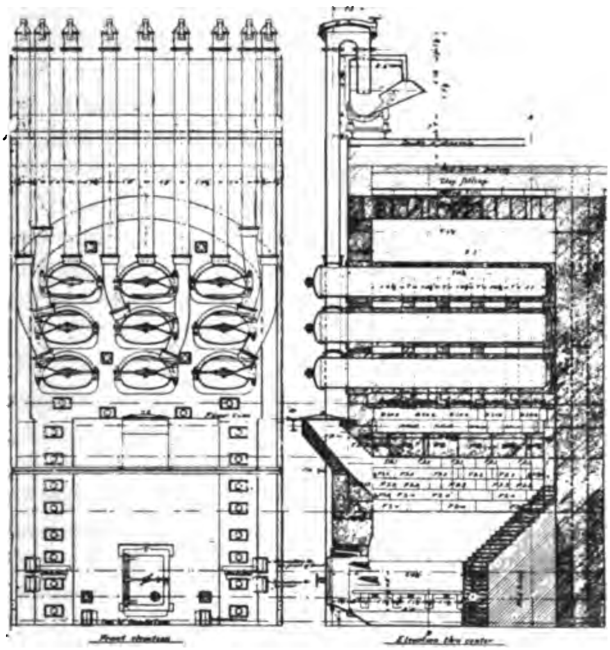
The practical extravagance of such a setting is at once apparent. Cold air enters through a shallow fire, burns to carbonic acid and steam, and the heated products pass around the retorts, and while still highly heated escape to the chimney. When the door is open for charging fresh fuel, which is usually hot coke withdrawn from the retorts, and when clinkering the fire, cold air sweeps over the fire directly around the retort, chilling it. Again, the combustion process is the one least suitable for surrounding, with combustible gases, retorts set some distance away, averaging 4 to 5 feet. Having but a short distance to travel through the fire, the conversion of the oxygen of the air into CO_2 is almost instantaneous, and the total heat of the chemical combination is confined to the fire, with the result that the fuel becomes heated to a temperature well above the fusing temperature of the ash. This rapidly seals off the fire, reducing the draft through it, and the combustion rate diminishes, cooling the setting, while the retorts are surrounded only by the products of combustion, and, except for the bottoms, immediately over the fire, get only the sensible heat of the products. Water is placed in the ash-pan so that a small quantity of steam rising therefrom may pass through the fire to assist in keeping down the

temperature of the fuel bed. This, while necessary to protect the grates, to a certain degree increases the difficulty, since the hydrogen thus formed burns at once to water at the top of the fire, further localizing the intensity of combustion immediately above the surface of the fire. The result is, that uniform heating of the retorts is difficult and uneconomical. Thirty years ago this style of setting was in wide-spread use. By having a large mass of fire-tile and small retorts, however, good results, as far as the quality of the gas was concerned, were obtainable.

The difference between heating a setting of retorts and a boiler fire, for instance, is readily understood. In the latter case combustion must have progressed to near completion before the combustible products impinge on the comparatively cold tubes or shell and combustion is arrested. In a setting of retorts, where all parts are kept at a temperature well above the ignition point of the most dilute gaseous combustibles, it is desired that the fuel bed should be kept at a temperature just sufficient to carry on the chemical reaction for the conversion of the atmospheric oxygen into carbon monoxide, and the final combustion of that gas occurs around the retorts situated at a comparatively remote distance above it.

The solution of these difficulties led to the adoption of the recuperative—sometimes called regenerative—method. Here there is a furnace below an arched chamber containing nine retorts exposed, except where supported, to the envelopment of heated products. This arched chamber and its contents of retorts is called a bench. Continuous arches so filled are called a stack of benches. The heated products of combustion on their way to the stack are led through passages made by thin fire-clay tiles; the primary air in its passage to the ash-pit, and the secondary air in its passage to the nostrils above the fire, pass around these tile flues, absorbing heat that was wasted in the former setting. Again, the fuel bed was deepened so that the oxygen on entering the fire, being first converted into CO_2, passes up through more fuel and becomes reduced to CO. We have now gaseous firing. There will be stored in the fuel bed only the heat developed by the combustion of carbon to carbonic acid, and there will be abstracted from the fuel bed the heat absorbed by the separation of the hydrogen from oxygen of the steam, the reduction of the carbonic acid to carbon monoxide, and the increase in the sensible heat of the escaping

atmospheric nitrogen. The top of the furnace is covered with a heavy covering of fire-tile built with an opening for the passage of the combustible CO diluted with N to the setting above. At this point, the highly heated secondary air combines with the gases from the fire and combustion at high temperature ensues. The fire, meanwhile, being deeper, has an arrangement by which false grate bars can be driven in at clinkering time, some distance above



Bench of Nine Retorts, with Full Depth Recuperators.
FIG. 3.

the fixed grates, holding up the fire while the clinker is being removed from between the false and fixed bars. There is also an arrangement by which small streams of water drip through the bottom of the fire, reducing the temperature further.

This method with care, gives satisfactory results, and is in extended use to-day. A further improvement in conditions is now obtained by returning a small quantity of the products of combustion through the fire, diluting the oxygen of the air and prolonging the period of combustion until all the retorts are bathed in flame.

Modern practice requires careful attention to bench heating. The per cent of combustible in the stack gases, the quantity of primary and secondary air are accurately read by meter and proportioned, and the heats of the combustion chamber and throughout the setting are noted at frequent intervals, with the result that uniform heats in the retorts at from 1700° F. to 1900° F. are maintained with an expenditure of fuel per ton of coal carbonized much less than formerly obtained. A retort, when discharged of its coke, should show a uniformly heated interior surface throughout—bright red in color.

The angle at which the retorts are inclined to the horizon is a question of much importance. But before we have sufficient data to take up a discussion of this question, we must look into what goes on inside the retort.

After a century of close study, it may be said, with regret, that not all of the details of the chemical reaction attending the conversion of coal into gas by the retort process are known at this time.

The process is considered as occupying three stages:

In the first one, a quantity (about 350 pounds) of cold, damp coal is charged into a retort 9 feet long and approximately 14 inches by 26 inches in cross-section; then there is a rapid cooling taking place on the inner surface of the retort. There is an absorption of heat by the coal, due to the high thermal head existent, and the heat rendered latent by the immediate evaporation of the water and the more volatile vapors in the coal. We know that the distillation begins on that portion of the coal in contact with the sides of the retort.

When coal is heated in a closed vessel at a heat of about 660° to 700° F., fusion of the coal commences and hydrocarbon vapors begin to come off. If these vapors were condensed, they would be found to be mainly paraffins and olefins.

The second stage ensues in which these hydrocarbons, meeting with the higher temperatures, begin to be affected. It is believed that there is a rearrangement and loosening of the C-H and the C-C bonds, and other compounds are formed. In the third stage the heat of the interior of the retort rises still higher, the reactions, almost instantaneous in many instances, are most complex, and so far have resisted entire elucidation. The aliphatic hydrocarbons, that is, the open-chain series, paraffins and olefins, as found in gas coal and petroleum, are, on the one hand, loosening their

carbon bonds and splitting off the initial or simplest members of their series, while the residues unite into more complex closed-chain or aromatic compounds, such as benzene, toluene, xylene, etc. These benzol compounds, under the influence of heat, in time are decomposed with the liberation of hydrogen, carbon and the formation of still higher ring compounds. On the other hand, the free hydrogen present reacts on the aliphatic hydrocarbons. In the meanwhile, the oxygen and the nitrogen in the coal are forming other combinations, some of the nitrogen going into ammonia and some of the oxygen uniting to form phenols.

A West Virginia coal would have a hydrocarbon component that is expressed as approximately $C_{519}H_{418}O_{50}$.

This third stage is the one which does most to determine the candle-power and heating value of the gas obtained. The retort is filled to about 40 per cent of its volume with coal. After the water and first vapors are driven off, the coal continues to fuse and the evolution of gas becomes more rapid, and, passing above the coal, is exposed to the highly heated sides and top of the retort. The hydrocarbons and other vapors pass off in gradually decreasing proportion during the distillation period of the charge, which we are now considering as being of about 4 hours' duration, and as the volume becomes less the energy expended on them diminishes and the retort gradually increases in temperature toward the end of the period, at which time, the temperature being higher, the flow of gas slower, the effect produced upon the gas is constantly changing.

I have so far asked your attention to the consideration of that form of modern retort setting in which the charge of coal is distilled in the shortest time, generally 4 hours. This design, being only a mechanical improvement upon the century-old chemical distillation of coal—an improvement looking toward economy in heating the bench and procuring more "even" heats, except so far as those bettered conditions could—did nothing to improve the chemical reactions. The distillation of coal is still conducted under very different conditions at the beginning than at the end of the period, and the gas emanating from the coal in the back of the retort is exposed to different heating conditions than that in the front.

Avoiding a too technical and voluminous discussion of these changes, it will still be well for me to make a simple statement

of the most important changes occurring in this third stage of how vapors of the paraffin and olefin series, which are those coming from the second stage, are affected by the temperatures of the retort.

It is doubly important to the gas engineer, because the same reactions occur in a water-gas apparatus or in an oil-gas plant, where paraffin base oils are subject to the "cracking-up" process. It constitutes one of the chief sources of interest and study of the gas engineer, and a better knowledge is sure to be rewarded by more economical operation of a gas plant, a better profit and improved product.

The higher members of the paraffin series and olefin series break down even at temperatures below their boiling points, under normal pressure, to lower hydrocarbons of the same series, and the paraffins to some extent are converted into the olefin series. Under continued exposure to these high temperatures, the lower paraffins and olefins are converted into members of the benzene series with deposits of free carbon; if the heat still continues there is a production of acetylene, followed at once by a breaking down into marsh gas and a large deposit of free carbon. Benzene (C_6H_6), the lowest member of the benzene series, at ordinary temperatures exists as a vapor. It has a high illuminating value, and, in water gas made from some oils, contributes largely to the illuminating power, though not so much to its heating value.

It is clear that the "cracking-up" process cannot go beyond the benzene-forming period without disastrous effect on the value of the gas, and it is true, further, that the formation of the benzenes are a loss in candle-power value over what would have occurred if the olefin gases, such as ethylene, had not been broken up. In other words, if we could convert the paraffins and olefins all into members of the olefin series, gaseous at ordinary temperatures, the highest efficiency would be realized, but in the rush of gas through the retort all the reactions are taking place at once. While some of the heavy paraffins and olefins are breaking down into lighter members of the same series others are being converted into benzols, while some of the benzols are going into hydrogen and free carbon. We must, therefore, use a heat which will crack up all the heavy paraffins and olefins, remove the gas before the final general breaking down occurs, and expect some losses in the process.

The difficulties that the coal-gas engineer has to meet are now

evident. He must maintain a heat in his retorts that will secure the proper "cracking up" of the heavier rush of gas in the first hour, and he must expect, in the form of retort under discussion, that there will be, toward the end of the carbonization period, too great an exposure to the heat of the smaller volume of gas, breaking down into free carbon and methane—a non-illuminating gas.

Other designs of retort settings suggest themselves as better than the one we have so far discussed. Instead of withdrawing the coke from the same door through which the coal was charged, retorts are used in many installations which open at both ends. The coal is charged into the retort until it is nearly full, and the coke is

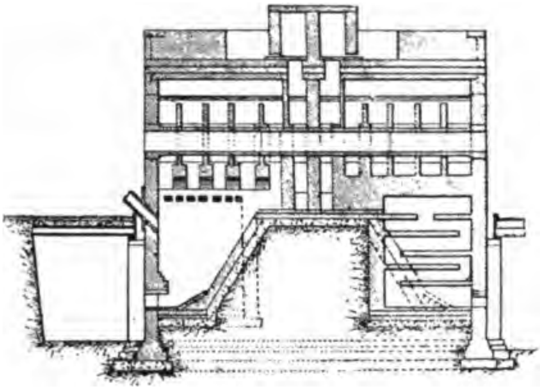


FIG. 4.—Retorts.

pushed out through the other end, the operation of pushing the coke out and recharging the retort being done by machinery in one motion. By this means the gas from the coal flows through the retort more rapidly; by reason of the smaller area existing between the coal and the top and sides of the retort, the temperature of the retort is reduced and a longer time is given for the carbonization period. There is still, however, direct exposure of the gas to the radiant heat from some portions of the retort.

Another development is in the vertical retort. Here the coal is charged into the top and the coke taken from the bottom of a vertical retort, which usually tapers to somewhat larger at the bottom. Here the coal is fused, filling the retort; there is no appreciable amount of space between the coal and the sides of the retort for the gas to be highly heated, and the gases must flow, in a large

part at least, up through the central unfused core of the coal itself, thereby escaping the difficulty under discussion. That there is less breaking down into free carbon, marsh gas and hydrogen in the vertical-retort process than in the horizontal is apparent by the smaller percentage of free carbon extracted from the gas by the tar in the after processes. The coal is raised to a greater altitude than in the horizontal retort, and when charged into the mouth at the top, which by machinery can be done with little labor, falls of its own weight out of the bottom as coke. Vertical retorts are

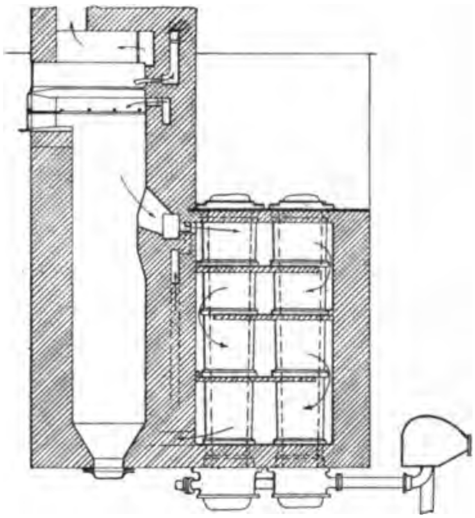


FIG. 5.—Vertical Retorts.

in wide use in Europe, having superseded inclined retorts, which do not appear to suit the theoretical conditions as well as the verticals.

The coke oven is another attempt at the solution of the problem of getting uniform, moderate heat throughout the body of the coal and throughout the carbonization period. It is, in effect, a large "double-end" horizontal retort in which large quantities (6 to 8, sometimes 10 tons) of coal are exposed to carefully graduated but moderate heats for from 20 to 36 hours.

What effect upon the cracking up of hydrocarbons, of temperature versus heat has, can hardly be discussed by me now. What is the relative effect of long-continued exposure to moderate temperature, to quick exposure to high temperatures? Some of our leading

developers of the chemistry of gas manufacture, notably the veteran Young, probably the most original, as he was the pioneer in this field, maintain that radiant heat has a very different effect on "cracking" than conducted or convected heat.

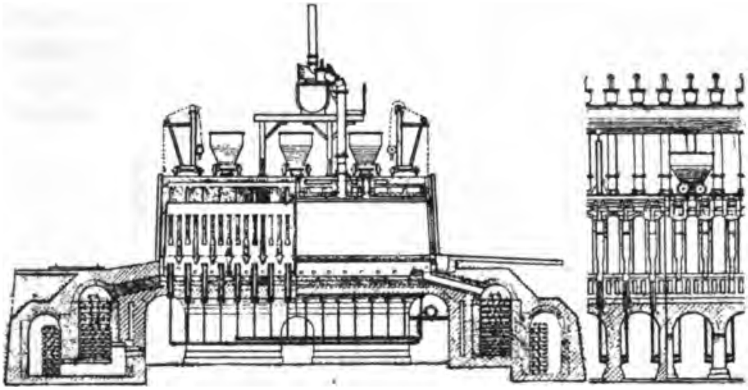


FIG. 6.—Otto-Hilgenstock Coke Oven. Regenerative Type.

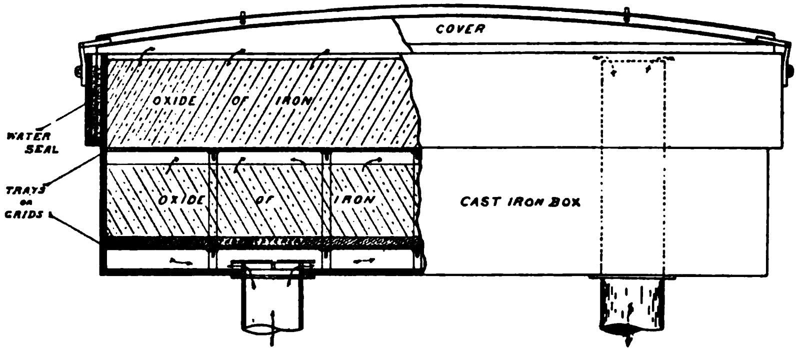


FIG. 7.—Sketch of Purifier.

Purification of Coal Gas

The principal impurities in coal gas, which must be extracted before the gas is fit for commercial use, are tar, ammonia, sulphur and sometimes cyanogen. In connection with purification the subject of condensation will be treated.

The fundamental principle of condensation is to reduce the gas, during its passage through the works to a proper temperature, so that in its distribution through the gas mains to the consumers'

appliances no vapors will condense out of it. In other words, after proper condensation at the works, the gas is, generally speaking, in a permanent fixed form for the ordinary conditions of distribution.

The principles employed in condensing coal gas are as follows:

First, gradual reduction in temperature down to about 110° F. Above this point, as much of the tar as collects in the hydraulic main and foul mains is allowed to pass off into the tar well. If coal gas at or below 110° F. is allowed to remain in contact with

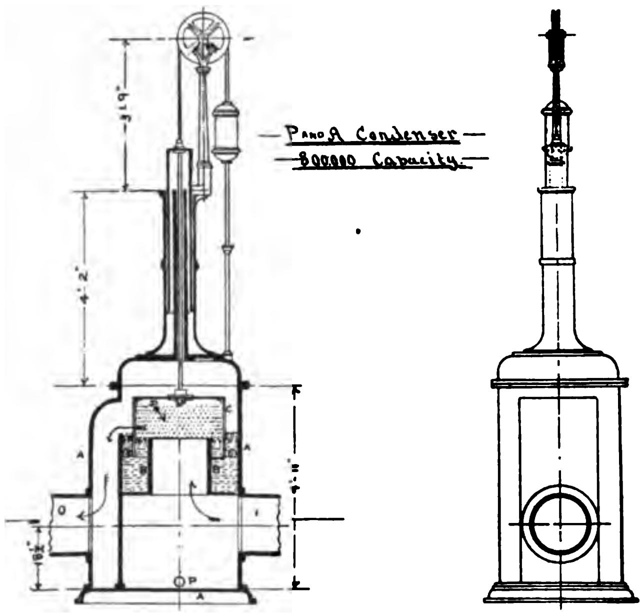


FIG. 8.

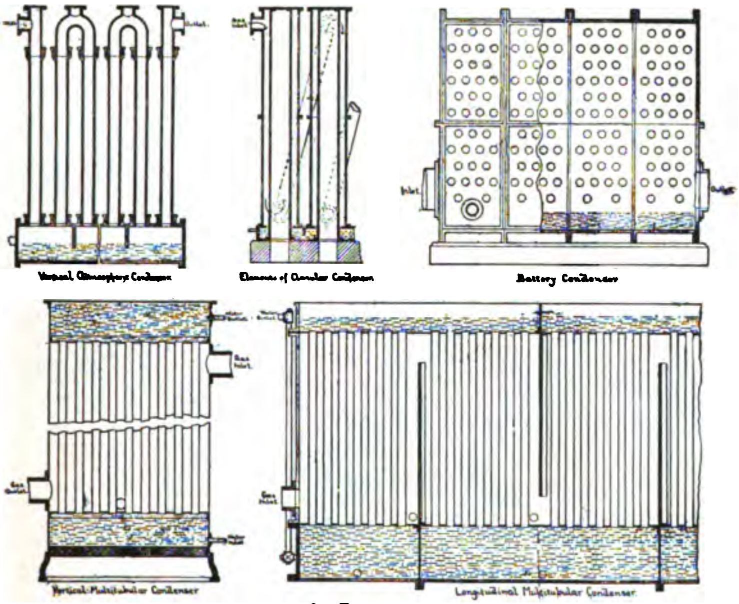
coal-tar a great amount of the heavy hydrocarbons in the gas are absorbed by it. By draining the tar off at proper points in the process, the benzol and other heavy vapors are retained in the gas.

Some tar is always carried with the gas through the various works pipes, and serves to absorb excess naphthalene vapors.

After the primary condensation down to about 110° F., a further extraction of tar takes place. This is accomplished in various ways, such as hot washing, or scrubbing, by centrifugal force, or mechanically, as in a P. & A. tar extractor, where the particles of tar are projected by high velocity against metal surfaces, where they are deposited and run off.

The condensation principle of gradually cooling the gas is important, as this prevents the sudden shocks to the gas, with attendant losses of valuable hydrocarbon vapors. Certain hydrocarbon vapors possess the property of apparently carrying other hydrocarbon vapors in a so-called state of suspension, up to the saturation point, which varies with the temperature.

Naphthalene, Coal Gas. The subject of condensation would be incomplete without brief reference to naphthalene. Its formation is believed to be principally due to the latter-day high heats of



Condensers

FIG. 9.

carbonization, and where it occurs in quantities it becomes exceedingly troublesome. Recently, washing the gas with certain oils has proved very successful. In mixed coal- and water-gas plants naphthalene is very readily handled, owing to the fact that the rich hydrocarbons in water gas absorb and carry it along.

The mechanical principle employed in condensers is simply the transmission of the heat, either sensible or that freed by reason of the latent heat of condensation of vapors, through steel, usually tubes, to air or water which are used as the mediums for absorption.

Ammonia is extracted from coal gas by the well-known principle of the power of water to absorb it. The mechanical methods of doing this are by so-called washing and scrubbing. In the earlier stages of the process it is advisable to wash or scrub the gas with crude ammoniacal liquor, which assists in removing tar, CO_2, H_2S and CS_2 from the gas. The crude liquor also extracts ammonia. Of course, the final traces of ammonia are eliminated by the use of fresh water.

Sulphur exists in crude gas as H_2S, and also organic compounds, the latter being largely CS_2. Washing or scrubbing the gas with

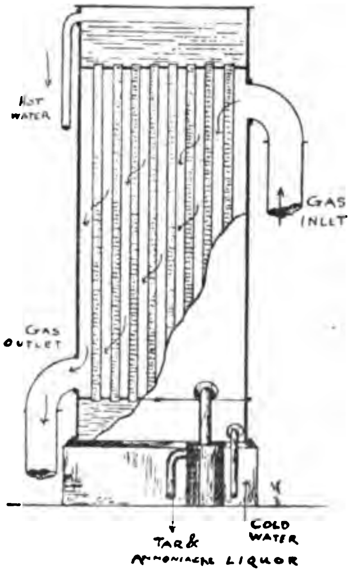


Fig. 10.—Water-Cooked Condenser.

crude ammoniacal liquor extracts a portion of these compounds, which form various chemical combinations with NH_3. A recent system of treating the gas, called the Feld system, eliminates usually by far the greater portion of H_2S, also some organic sulphur is removed in the purifiers.

In the United States iron oxide is used in the usual system of purification. The H_2S in the gas combines with the iron oxide to form iron sulphide. The "fouled" material, by exposure to air, revivifies, the oxygen of the air combining with the iron sulphide to form iron oxide, leaving the sulphur in the material in the free state.

The free sulphur probably does extract a certain amount of CS_2 from the gas, as CS_2 dissolves sulphur.

In England the hydrated form of quicklime is employed. This process removes CS_2 as well as H_2S, but is not much used in this country on account of the expense.

Carburetted Water Gas as Made from Fixed Carbon, Steam and Oil

It is not the intention to present for your consideration mere history, but a brief reference to the development of carburetted water gas may not be out of place, and will probably assist in the clearer understanding of the principles underlying this process.

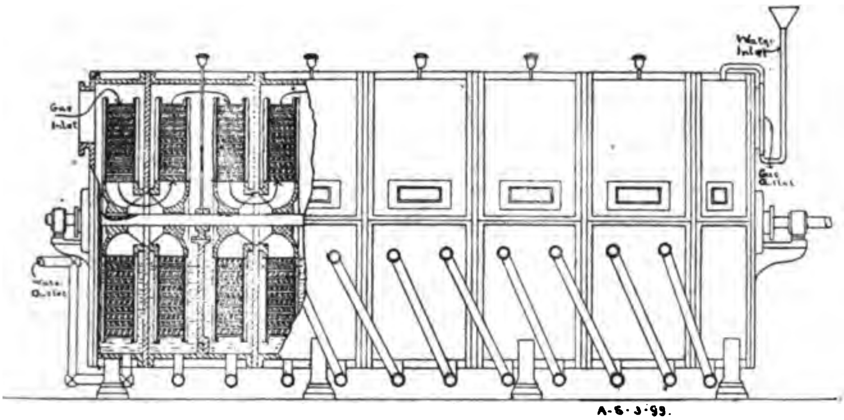


FIG. 11.—Plate No. 2—Rotary Scrubber.

The fundamental chemical principles underlying the process of making this gas from fixed carbon, steam and oil are comparatively simple. In the first place, there is a bed of fuel, brought up to high temperature, which we may call incandescent carbon for the purposes of this lecture. Steam is admitted and passed through this fuel, and, as is well known, decomposes into its elements hydrogen and oxygen in the presence of incandescent carbon. To give you an idea of such reactions, and the approximate minimum temperatures at which such decomposition takes place, whether in the presence of incandescent carbon or not, the following table is shown:

$H_2O \longleftrightarrow H + O$. Min. temp. about 1000° Cent. — 1200° Cent.

$H_2O + C = CO + H$. Min. temp. about 600° Cent.

From this you will note the comparatively low temperature required to decompose H_2O in the presence of incandescent carbon.

The result of this reaction, which takes place in a fire-brick-lined vessel called a generator, is the formation of so-called blue or uncarburetted water gas, which consists principally of carbon monoxide and hydrogen, and burns with a blue practically non-luminous flame, and has a calorific value of about 320 B. t. u. per cubic foot.

This blue gas then passes into a fire-brick-lined vessel filled with a checker-work of fire-brick, which has been heated to incandescence. A spray of hydrocarbon oil is admitted above this checker-brick, is vaporized and gasified by the heat, and mixes with the blue gas previously described. The oil furnishes the illuminants necessary for candle-power, and from the analysis submitted in the early part of this lecture, it will be seen that a good calorific value is also obtained. The candle-power and calorific value depend very largely upon the relative quantities of blue gas and the gas resulting from the decomposition of the oil.

The mixture of blue and oil gas is subsequently subjected to a so-called "fixing" process, by being passed through an additional amount of heated checker-brick, the effect of which is merely to render the various hydrocarbon gases more permanent under ordinary temperatures, probably by the reason of the decomposition or partial decomposition of some of the richer hydrocarbons into the simpler and more stable forms.

Development of Water Gas

The production of water gas has been attempted in three ways:

First. In the earlier forms it was attempted to produce water gas by contact of steam with heated coal or coke contained in a retort externally heated, as is illustrated by the Harris patent.

DESCRIPTION OF THE HARRIS PATENT

A bench of three clay retorts, shown in Figure 1, was used. Retort A, or the decomposing retort, was provided with a perforated tile (Fig. 3). The retort was filled above the tile with anthracite coal broken to the size of an egg.

Retorts B and C were filled with rich cannel coal. Figure 2 shows a cross-section of the decomposing retort. Figure 4 illustrates the steam drier which was placed near the base of the furnace. Figure 5 represents the steam superheater.

Steam supplied from a boiler heated by the waste gases from the bench was first passed through superheater E into retort A,

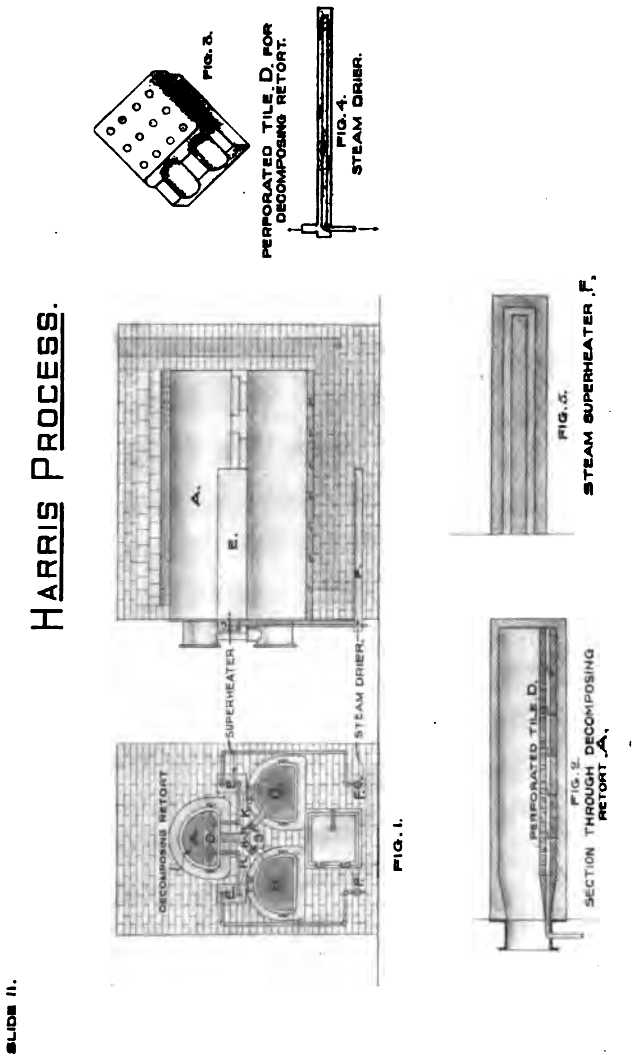

SLIDE II.
HARRIS PROCESS.
FIG. 3.
PERFORATED TILE D. FOR DECOMPOSING RETORT.
FIG. 4.
STEAM DRIER.
DECOMPOSING RETORT
SUPERHEATER
STEAM DRIER
A.
E.
FIG. 1.
FIG. 5.
STEAM SUPERHEATER F.
PERFORATED TILE D.
FIG. 2
SECTION THROUGH DECOMPOSING RETORT A.

FIG. 12.

passing through the distributing tile D into the highly heated anthracite coal. Leaving this retort the gas was conducted to the rear end of either of the lower retorts, B and C, through pipes H, and from this retort through stand-pipes K to the hydraulic main.

The gas from the decomposing retort was supplied to one bituminous retort until the rich hydrocarbon vapors of the charge in this retort were exhausted.

This retort was then closed off by means of cock 3 and the gases from retort A were then passed to the other, etc.

Retorts B and C were charged at intervals of about 2 hours. These attempts were unsuccessful, but your attention is directed to them to illustrate the basic principles. Various patent applications, from time to time, show the recurrence of this idea in different men's minds. The reason of the failure of this process is because the chemical reaction of steam upon the fixed carbon of the incandescent coal or coke is an endothermic one, in other words, one which absorbs energy in the form of heat, and requires much more heat to maintain it, and more intimate association of the steam and coal or coke than can be obtained in this way.

Second. The next step in the process is embodied in the ideas formulated by Tessie du Motay. In general, this process consists in making blue-water gas intermittently in a generator and storing same in a holder.

The apparatus consists of generator A, gas-relief holder, bench of retorts with furnace C, retorts D, hydraulic main E, and naphtha vaporizer B.

The generator is filled with anthracite coal or coke, through which steam is passed, after this bed of fuel has been brought to incandescence; the resulting gas being a blue-water gas, largely CO and hydrogen, this gas being passed along to the relief holder for storage. The bench of retorts having been brought to the proper heat for vaporizing, the oil gas is admitted to the front end of retorts at point "H," and at the same point naphtha vapor is admitted, the naphtha having been vaporized in vaporizer "B" by means of steam coils or otherwise; the naphtha vapor and blue-water gas are each regulated at this point, "H," to produce the proper candle-power of gas, and passing through the retorts "D," coming in contact with the heated surface is sufficiently heated to be largely converted into a fixed gas, passing off at the opposite end of the retorts to the hydraulic main, afterwards treated in a

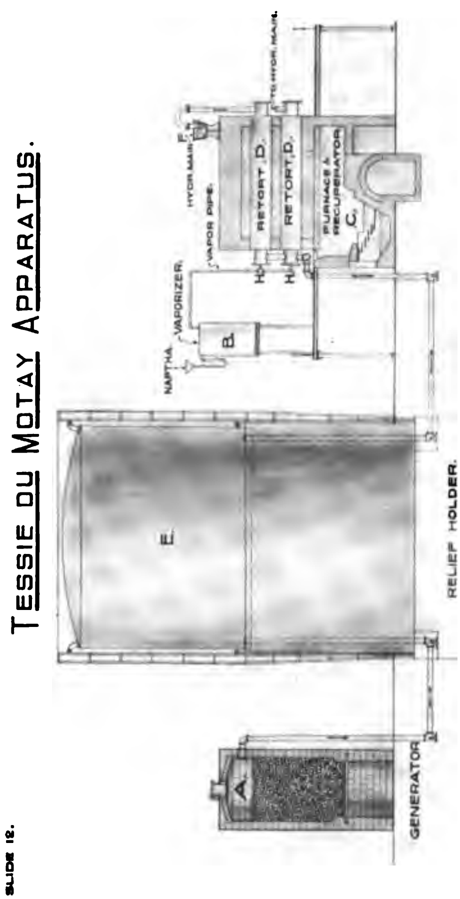

SLIDE 12.
TESSIE DU MOTAY APPARATUS.
GENERATOR
A.
E.
RELIEF HOLDER.
NAPTHA.
VAPORIZER.
B.
VAPOR PIPE.
HYDR. MAIN.
F.
RETORT D.
RETORT D.
H.
H.
FURNACE & RECUPERATOR
C.
TO HYDR. MAIN.

FIG. 13.

similar manner to other gases. In operating, the generator was first brought up to heat by blowing sufficient air through a bed of fuel to raise this bed of fuel to a high temperature. When the fuel was hot enough, the blast was cut off, a valve closed and steam admitted, which, on passing through the fuel, resulted in the production of blue-water gas. The endothermic action of decomposition of steam in the fuel bed resulted in a rapid cooling of the fire. When the fire temperature became so low that the steam was no longer readily decomposed, the admission of the steam was discontinued, and the blast turned on again, as before, and the cycle of operations repeated.

In the meantime hydrocarbon oils were being vaporized in a separate apparatus, and these vapors, mixed with the blue-water gas, were passed through an apparatus externally heated, wherein the gas was "fixed" or rendered permanent.

The limitations of this system of gas manufacture were that the oils which could be vaporized were the refined fractions of crude oil, called naphtha, and as these oils rapidly advanced in price the limit of economical operation on a commercial scale was soon passed.

The Lowe Process

Third. The Lowe process. This method, or modification of it, is the one in use to-day. To describe its essential principles it is advisable to insert a short description of the apparatus used. A Lowe water-gas set, or its equivalent, consists of—

First. A generator, or vessel built of an iron shell with a fire-brick lining, and containing a deep bed of fuel.

Second. A carbureter, or vessel consisting of an iron shell lined with fire-brick, and filled with a checker-work of fire-brick. This vessel has an open chamber at the top into which the oil is sprayed.

Third. A superheater, or vessel built and checkered similar to a carbureter.

To explain the operation of such a set we will first assume it cold, but with a coke or anthracite fire started in the generator. By means of a blower an air blast is turned under this fire, and the carbon in the fuel bed burns partly to CO_2, partly to CO. The CO_2, on passing through the incandescent fuel bed, is practically wholly decomposed to CO, the amount depending on blast velocity, temperature, etc.

When the producer gas (for such it is) reaches the top of the generator above the fire it consists principally of N, CO and a small percentage of CO_2. By means of a large fire-brick-lined connection this producer gas is conducted to the top of the carbureter. Here an additional blast opening introduces fresh air, and a portion or all of the CO in the producer gas burns to CO_2 in the carbureter. The resulting mixture passes out of the carbureter, and into the bottom of the superheater, where still another blast admits enough air to burn the remaining CO to CO_2, in case it is desired to heat the superheater higher, but if not, no further air is admitted here. The final waste gases then pass out of the stack valve at the top of the superheater and escape into the atmosphere, or are first passed through some apparatus to abstract as much of the remaining sensible heat as possible. This process of blasting or blowing is continued until the entire fuel bed is highly incandescent, the checker-work in the carbureter at a high heat, and at a reduced temperature in the superheater. The set is then ready to make gas.

The blast is first shut off from all of the vessels, and the stack valve on the superheater closed, live steam is then turned into the generator below the fire. The resulting reactions are very instructive. The H_2O vapor is first decomposed by the incandescent carbon to hydrogen and oxygen. This reaction is endothermic, that is, heat is absorbed in doing this work. The hydrogen passes through the fire unchanged.

The oxygen, on the other hand, immediately combines with carbon to form CO and CO_2, and every pound of carbon thus burning to CO_2 gives off about 14,544 B. t. u., the reaction being exothermic. The CO passes on through the fire, but the CO_2, in the presence of the incandescent carbon, decomposes to CO, the reaction being endothermic.

The gas appearing on the top of the fire, then, is a mixture of hydrogen and carbon monoxide, in practically equal proportions, together with a small percentage of CO_2 and some impurities. This mixture is the so-called blue or uncarburetted water gas, and is merely one form of producer gas, having a calorific value of about 320 B. t. u.

It will be noticed that the reactions in the generator are mostly endothermic, and, in fact, the fire is cooled very rapidly during the admission of steam, a run being generally from 5 to 10 minutes, at the end of which it is necessary to blast again.

Coming back to the blue-water gas, so-called because it burns with a blue flame in air, we find upon leaving the top of the generator that it passes into the top of the carbureter. Here it meets with a spray of oil. This is sometimes the crude oil, but more often a gas distillate, which is the fraction obtained from crude oil after distilling off the gasolines and kerosenes, and stopping before the heavier lubricating oils appear.

This oil, coming into the top chamber of the carbureter, vaporizes under the intense heat and, mixing with the blue gas, starts through the carbureter. The lower portion of the carbureter and the superheater are merely heated checker-work for rendering the gases permanent under ordinary conditions, or "fixing" it, as it is called in operative parlance.

Crude petroleum consists of a mixture of a great number of definite hydrocarbons, that is, hydrocarbons that may be designated by exact chemical formulae, but which are so almost inextricably mixed in the oil that the separation of any one of the hydrocarbons in considerable quantities requires repeated distillations under favorable conditions and chemical treatment.

Crude oils are designated as paraffin base, semi-paraffin base and asphalt base, according to the general character and composition of the oil.

Paraffin-base oil, as I have stated in discussing coal-gas manufacture, is one made up almost entirely of members of the paraffin and olefin series. Paraffins from simple CH_4 methane to pentatricontane $C_{35}H_{72}$ have been isolated; methane CH_4, the simplest member existing as a gas; pentatricontane ($C_{35}H_{72}$), as a solid, melting at 76° F. This oil is found in the northern oil districts, such as Pennsylvania and Ohio.

Semi-paraffin-base oil contains, in addition to paraffins and olefins, naphthenes (C_nH_{2n}). These compounds have the same chemical formulae as the olefins, but have markedly different characteristics. The explanation for this is in the way that the C and H atoms are united, differing in the two series, the carbon particles in the olefins existing as a simple chain, whereas the naphthene carbon atoms are considered as being grouped as a closed ring. This class of oil is found in southern districts, like Louisiana and Oklahoma.

Asphalt- or naphthalene-base oils are made up largely of naphthene and olefins, paraffins being almost entirely absent. Examples

of this kind are found in Texas and California. The naphthene series are much more stable than the paraffin; they do not yield paraffins or olefins in cracking under heat, but pass at once into members of the benzene series, such as benzene, toluene, xylene and higher members. These benzenes exist in the gas only as vapors, and are subject to the laws of vapors regarding saturation and precipitation; consequently, gas made from naphthene oils must be very carefully handled in the processes subsequent to generation to secure to the consumer equal candle-power at all seasons of the year. For additional information on the treatment of this gas I would refer you to a paper presented to the American Gas Institute by W. H. Gartley in 1907.

The results of gasifying the oil show that the various hydrocarbons evolved depend, as to nature and relative quantities, on time, temperature, relative quantities of oil injected, and amount of heat available from the fire-brick. The richer illuminants predominate, of course, and this rich oil gas, mixing with the blue water gas, results in carburetted water gas, and which has a high candle-power and calorific value. By varying the relative quantities of blue gas and oil gas, and the heats, time of run, etc., the candle-power and heating value may be made high or low, as desired. The maximum and minimum limits would be about as follows: With no blue gas and all oil gas, the candle-power would be about 85, and the calorific value about 1300 B. t. u., or, with all blue gas, and no oil gas whatever, the candle-power would be practically zero, and the calorific value about 320 B. t. u. Any intermediate condition could be attained, but in practice it is found that a gas exceeding 26 to 30 candle-power, burns with a smoky flame in ordinary burners, under usual conditions, and, furthermore, the tendency of the present time seems to be towards a standard gas of an average of about 600 B. t. u. calorific value.

When a water-gas set has been making gas for a certain number of minutes it becomes too cool for economical operation. The oil is then shut off, next the steam, and then the stack valve is opened. Thereupon the blast is turned under the fire and the whole cycle of operations is repeated.

On account of the steam striking the under side of the fire and cooling it too rapidly, it is now customary to make a so-called "down run" every third or fourth time. This simply means that the direction of flow of the steam through the fire is reversed, now

passing downwards instead of up, the connections on the machines being so arranged as to permit of this being done. As often as the fire requires it, fresh coke or coal is put into the generator, the ashes and clinkers being taken out at the bottom.

From the description given of the principles involved in the Lowe process it will be seen that it is essentially an intermittent one. In the first place the deep fuel bed is brought up to a high temperature in the most economical way, namely, by internal combustion in the generator, and in this way differs from the early processes first mentioned.

Secondly, it differs from the second type, or that promulgated by Tessie du Motay, in making use of the heat from the generator gases to vaporize and fix the oil.

These differences may be seen from the basic claim of the Lowe patents, which, in brief, are as follows:

Basic Claim Lowe Patent

The apparatus consists of the primary gas generator A, superheater D, heat-restoring stack I, boiler R, the usual washer V, and scrubber Y.

The gas generator A is filled with anthracite or bituminous coal, air is forced by a blower through the heat-restoring stack I and pipe L into generator A below the grate bars, having been preheated in passing through stack I.

The products of combustion are conducted from the top of generator A through pipe F, through the superheater, which is filled with loose fire-brick above the arch, to the atmosphere through stack I, Valves E′ and H having previously been opened.

The heat from the out-going gas is partially transferred to the air from the blower, which is forced around the stack tubes into pipe L. After the fuel in the generator is thoroughly incandescent and the superheater is heated, the air is cut off and the valves E and H are closed.

Steam is now admitted into the top of the superheater through E′ from boiler R.

The steam in passing through superheater becomes intensely hot, and is admitted to the generator below the grate bars through pipe H′. The steam in passing through the heated carbon is decomposed, liberating hydrogen and producing a proportionate quantity of CO_2. The CO_2 in passing through the heated carbon is, for

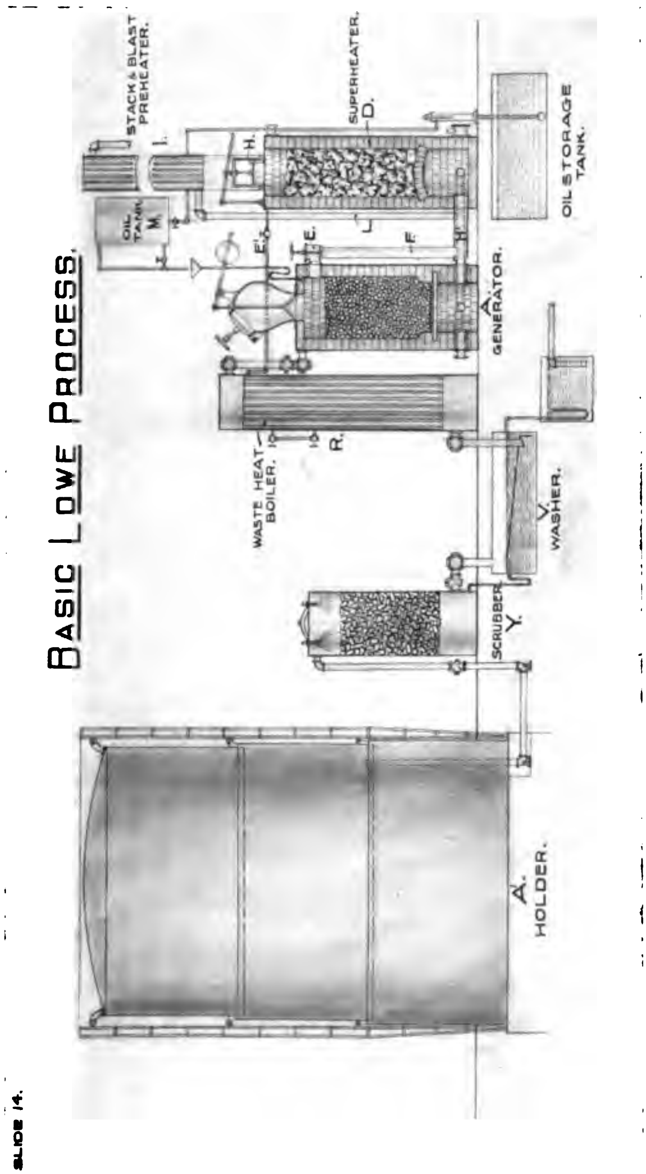

BASIC LOWE PROCESS.
STACK & BLAST PREHEATER.
I.
SUPERHEATER.
D.
H.
OIL TANK M.
E'.
E.
F
L
A.
GENERATOR.
OIL STORAGE TANK.
WASTE HEAT BOILER.
R.
V.
WASHER.
SCRUBBER
Y.
A.
HOLDER.
SLIDE 14.

FIG. 14.

the most part, changed to CO, and the gas at the top of the fuel bed is H, CO and a small part of CO_2.

At the same time steam is admitted to the superheater, petroleum or other hydrocarbon oils are introduced in regulated quantities from tank M on to the top of the hot coals in the generator, where it is volatilized and mixes thoroughly with the gas coming through the fuel bed. These gases are then fixed by the heat before leaving the generator from which they pass to the top of the boiler R through numerous tubes, transferring some of their sensible heat to the water. All of the steam used for the gas-making process is furnished by this boiler, and the heat of the gas is the only energy used for generating the steam.

Passing through the boiler the gas enters the washer V, thence through the scrubber Y into the purifiers, and finally into the holder A′.

It should be stated that this apparatus never worked satisfactorily for the reason that the oil gas was not subjected to sufficient heat to fix it into a permanent gas. Mr. Lowe later changed his method, although conforming to the original patent, and substituted in place of the superheater for drying and superheating the steam, a superheater filled with checker-brick properly heated by internal combustion in the superheater of the producer gases formed in the generator at the time of blasting up the heats. When making gas the blue water gas from the generator, with the oil vapors generated at the top of the generator, pass through the superheater for the purpose of fixing the oil vapors; this principle being the same as that employed in all water-gas-making apparatus up to the present time.

Returning for a moment to the original table giving composition of gases, it may be stated that the illuminants methane and ethane, result from gasifying the oil, while the carbon monoxide and hydrogen result from the action of steam upon the incandescent fixed carbon in the generator fuel. The balance of the constituents result from both sources, but to a varying extent.

The subject of the efficiency of a Lowe water-gas set as a heat machine may be stated practically about 60 per cent. The subject is too lengthy to be discussed here, but anyone interested is referred to a paper by Mr. A. G. Glasgow, Proceedings American Gas Light Association, 1890, or to an abstract thereof which appears in the "Mechanical Engineers' Pocket-Book," by William Kent, under the general subject of illuminating gas.

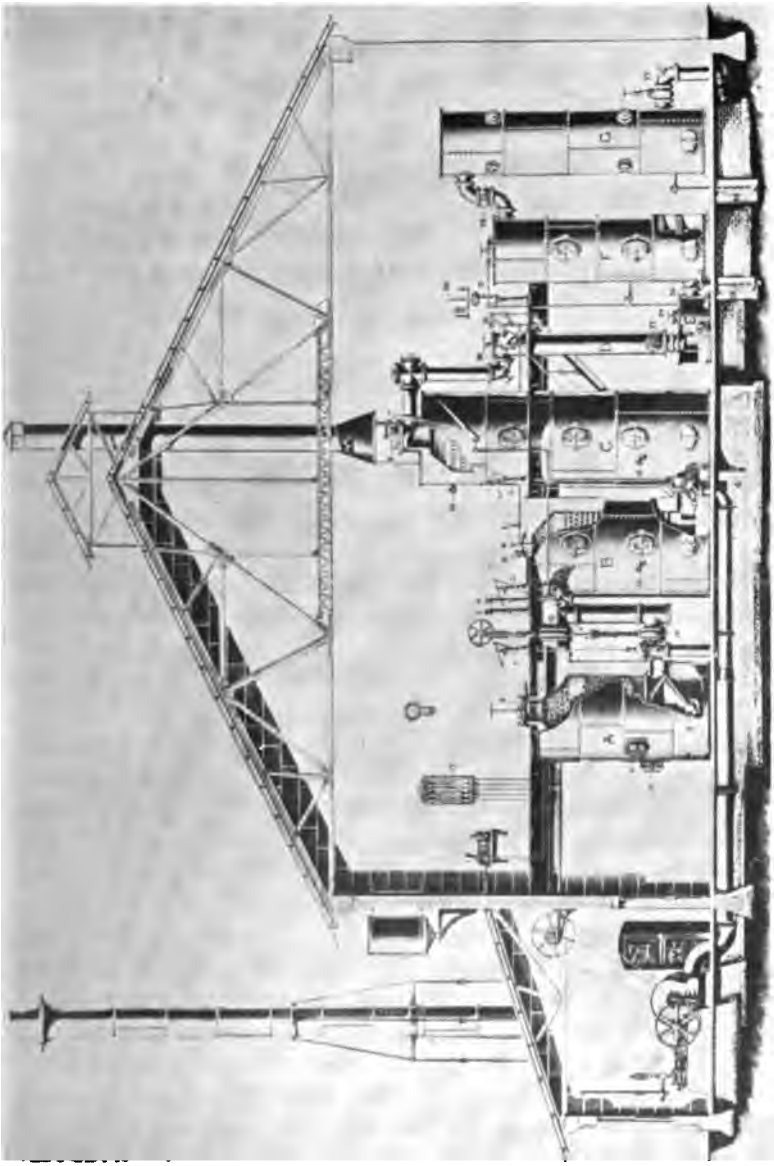


FIG. 15.

In general, we may use the following average figures to illustrate the efficiency of a Lowe water-gas set, all per thousand cubic feet gas made reduced to 60° F.:

Pounds anthracite generator fuel	30
Pounds oil admitted to carbureter	32
Pounds steam used during run	30
Pounds resulting gas produced	46

This serves to introduce the principles of water-gas manufacture, and we will now discuss the subject of treatment of this gas after leaving the generating apparatus.

Purification of Water Gas

Coming to the subject of impurities, we find that tar and sulphur are the predominating ones that must be abstracted. Before treating these, however, it is to be remarked that water gas is to be condensed, in a measure, similar to coal gas. Water gas, however, in modern practice, is not reduced to as low a temperature in the works as is coal gas.

The principle of water-gas condensation, however, is the same as for coal gas. The heat to be abstracted consists of the sensible heat plus the latent heat of vaporization of the various gases and vapors which compose the gas. This results in deposition of some of the heavier hydrocarbons, forming the so-called water-gas tar.

In modern practice water gas is seldom condensed below 90° F., because its purification is most economical at this or somewhat higher temperatures, and also because more of the richer illuminants remain in the gas at the higher temperatures. A large amount of condensation takes place in the relief holder.

Naphthalene is easily avoidable in water-gas practice by proper regulation of the heats.

Tar is extracted from water gas by condensation, washing and scrubbing, and also by mechanical means, such as a P. & A tar extractor. With the oily water-gas tar, however, the P. & A. must be operated between rather narrow limits of temperature, say between 105° and 110° F., and under great differential pressure.

Usually, after all the washing and scrubbing, there remains a mist of light tarry vapors which are exceedingly difficult to extract. This is perhaps best accomplished by means of shaving scrubbers, in which light wood shavings simply absorb the mist as the gas slowly passes.

Sulphur exists again as H_2S and organic sulphur, and is usually removed by means of iron oxide as described under coal gas. In coal gas the purification is usually carried on under lower temperatures than in water gas, because in coal gas the gas is previously reduced to a low enough temperature to permit the extraction of the ammonia.

Carburetted Water Gas as Made from Oil and Steam Only

Lowe Oil Gas. There is time here only for a brief mention of carburetted water gas as made from oil and steam only. This process is more largely used on the Pacific slope on account of the low cost of oil and the high cost of coal and coke.

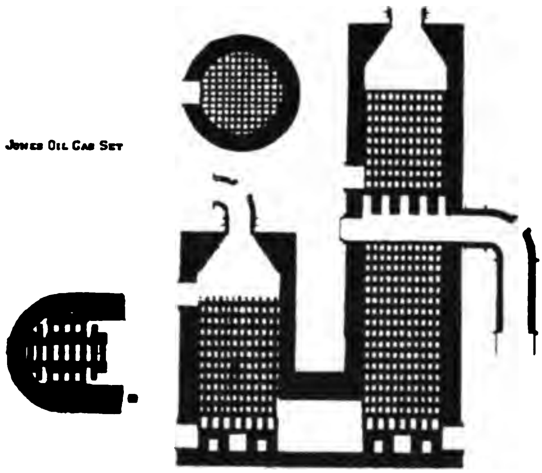


FIG. 16.

The development of this oil-gas process is due to the efforts of Mr. Lowe, as well as largely to Mr. E. C. Jones, Chief Engineer of The San Francisco Gas & Electric Company.

The principles underlying the manufacture of gas by this method are unique in a way. No standard type of apparatus has been developed, but there are various forms of one-shell and two-shell types in use on the Pacific coast to-day.

These shells are of iron, lined with fire-brick and checkered with fire-brick. To heat up the set oil is introduced, or sprayed in with a steam spray, and burns by means of an air blast, the products of combustion passing off through a stack valve in the usual manner.

When the set is up to heat the air blast is cut off, and the oil and steam admitted alone. An accurate adjustment of the quantity of oil to the heat is necessary for best results.

The oil gasifies under the heat of the fire-brick, and the steam is partially decomposed into its elements. Some of the heavier illuminants are decomposed, and considerable free carbon or lamp-black results. The gas produced, as will be seen from the early tables, resembles coal gas very much in its analysis.

The impurities to be removed from this oil-gas process are lamp-black, tar and sulphur. The lamp-black removal, handling and treatment is a problem in itself, but it is removed from the gas by washing with copious quantities of water, and by scrubbing, and is subsequently fired under the boiler in a wet state, or it can be used as generator fuel in an ordinary water-gas set.

The tar and sulphur are removed in the customary ways. Oil gas, as made above, is treated much like ordinary water gas, except it is *never* passed through condensers, but is subjected to much washing and scrubbing. This process of treatment at once appeals to anyone as being logical, on account of the large quantities of lamp-black made during its generation.

Under conditions of best practice to-day, this process of gas manufacture requires about a total of 7 to 8 gallons of oil per 1000 cubic feet made, and there is every likelihood that this quantity will be materially reduced. From general figures it would seem that only about 2 gallons of oil should be necessary to supply the required amount of heat, and if we figure an average of 4½ gallons for making the gas, it would seem as though from 6 to 6½ gallons will ultimately be all that is required for this process. Recent results indicate that these figures may be attained.

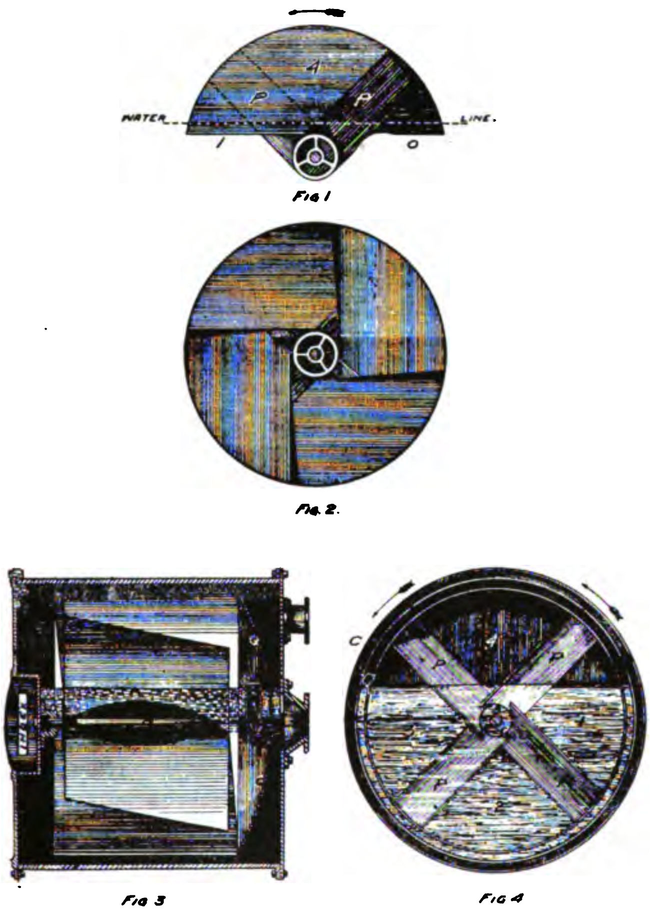
Producer Gas

Producer Gas. Producer gas is usually made by one or both processes already explained under coal- and water-gas manufacture. In some forms it consists of CO and N, produced by air being blown through a bed of incandescent fuel, the resultant gas having a calorific value of about 120 to 130 B. t. u. per cubic foot. If, in addition to air, we add steam, the resultant gas will contain H, CO and N. If steam alone is used the gas will consist of H and CO, and will have a heating value of about 320 B. t. u.

Gas, as an agent for the production of light and heat, must not be understood to be restricted to artificial gas, as before outlined,

but many other forms besides these mentioned are used, such as retorted oil gas, blast-furnace gas, acetylene, gasolene air gas, resin gas, wood gas, hydrogen-methane gas, garbage gas, etc.

Producer gas is only mentioned at this time on account of its adaptation to gas-engine practice.



STATION METER DRUM.
FIG. 17.

Metering Gas at Works—The Station Meter

Station Meter. The gas after passing through the purifiers is ready to sell, except that the amount made must be determined in order to keep the several parts of the works under control. This

measuring is usually done by means of a large four-compartment drum which revolves in a cast-iron case filled about two-thirds full of water.

The inlets and outlets of the drum compartments are so arranged that when the outlet is below water the inlet is above, and the compartment fills with gas. The drum revolves something like a squirrel cage, and shortly after the inlet dips below the water the outlet comes above and the compartment discharges its contained gas. The cubical contents of the compartments being accurately known, the motion of the drum is communicated by gearing to the dial, and thus we have an apparatus which accurately measures the gas made. It is customary to make proper corrections for temperature and barometric pressure, and in practice we reduce the gas manufactured to a basis of 60° F., and 30 inches barometric height.

On account of the large size of station meters various forms of proportional meters have been tried. These measure only a small fraction, usually 1 per cent, of the make, and are also arranged to register the total, but so far there is really no reliable proportional meter on the market for measuring artificial gases.

Recently various other methods of measuring gas have been tried. Drums have been made of the rectangular screw-thread type, rotary meters have been introduced, and the most recent is the electric gas meter. The time is too limited to attempt to explain these in detail.

Gas Holders

Gas holders are simply inverted cups placed in water, and so arranged that the gas enters or leaves the holder above the water through pipes arranged for the purpose. They act as storage reservoirs for gas, and thus allow the plants to manufacture uniformly during the 24 hours, taking care of constantly varying consumption. The only principles involved are as given, and the great questions involved in connection with gas holders, outside of their design and construction, are "How much gas-holder capacity is required as related to the maximum manufacturing capacity?" and "Where shall these holders be located—at the gas works or in other localities?"

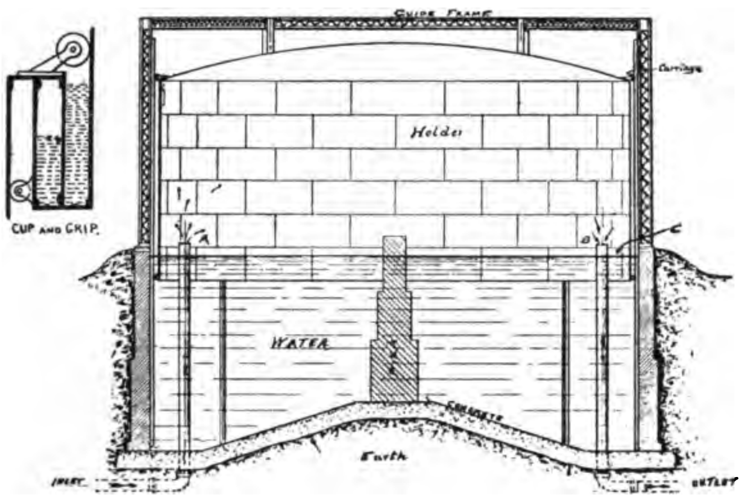
The latter question is largely a matter of distribution methods, and the former the question of the minimum permissible holder

capacity any plant may have and be safe. This is a very important engineering and commercial detail.

Distribution

In the distribution we have a vast subject, and one in which many problems remain to be solved.

Formerly gas was sent out from the works at not to exceed the maximum pressure thrown by the works holders. In such systems the delivery obtainable from a given size and length of pipe was



~SECTION~

FIG. 18.

that due to the differential head or pressure between the lowest permissible pressure at the extreme end of the pipe, say 2 inches water column, and the maximum holder pressure, which rarely exceeded 5 or 6 inches. Thus the actuating pressure, or differential head, was very little, possibly less than one-tenth of 1 pound per square inch.

Subsequently, as cities spread out, gas holders were erected in outlying localities and called district holders, and these supplied the district surrounding them, as before, by low pressure. These district holders were filled with gas through separate pumping mains from the works.

In the course of time these systems were found to be inadequate, and if re-enforced under the low-pressure ideas would have entailed

vast construction expenditures to remedy conditions sufficiently to produce good service.

To overcome bad distribution systems, especially in the larger cities, the next step in the progress of distribution methods was to erect pumping plants at the works and holders, run separate pressure re-enforcing pipe lines to the heavy points of consumption, and there install some device to automatically reduce the pressure to the required regular distribution pressure. In some cases pressure-indicating instruments were located at such points of heavy consumption, and no regulators used, the pressure and amount of gas pumped being controlled at the works and holders so that a given pressure was maintained at this point where the indicator was located. The instruments transmitted the amount of pressure back to the pumping plant, or a small separate-pressure tell-tale line was used. These systems used various pumping pressure, usually not over 5 pounds per square inch.

In the meantime still another development was taking place. Communities were growing and spreading out in all directions, and especially around the larger cities where suburban communities were being formed at some distance from the cities, and in which the houses were far apart. It was not possible to profitably supply such places with gas with the great investment required in low-pressure mains under the old system, so high pressure was developed to meet this requirement.

Pressures up to 50, 60 and even 80 pounds per square inch are now being used, as compared to the old system of low pressure, with a maximum of about ¼ pound. Such high pressure requires reduction to say 4 or 6 inches water column before entering the piping in the consumer's building, and this is accomplished by automatic gas regulators, a number of different types of which are now on the market.

Reasons for High Pressure. In the meantime other forces were at work tending to hasten the advent of high pressure. The uses to which gas was applicable were increasing in number, it was also used more freely in lighting, heating and power work, and this resulted finally in very much larger sales of gas per capita per annum than prevailed formerly. Add to this the fact that the price of gas was gradually being reduced and another stimulus is seen. Thus vast quantities of gas were being consumed as compared to former years.

The principles underlying the development of high pressure then resolve themselves into the fact that it was necessary to provide for vastly increased demand, and also that the distances through which it was necessary to supply gas in large quantities were greatly augmented.

This development was not rapid in the early days of the gas business, and, in fact, it may be said to have developed with the advent of fuel gas, the possibilities of which have only been realized within the most recent years. In fact, it may be said that the application of high pressure to artificial gas is a development of the last decade.

Higher pressure permits of small pipes to transmit large quantities of gas. The reasons for this are that the differential head is very much greater than under low pressure, and also a given mass of gas occupies a much smaller space when compressed.

The flow of gas, or any liquid through pipes, is governed by the differential head or effective driving pressure, the length of the pipes, its diameter, the condition of its interior surface, whether the line is straight or full of turns, the density of the traversing gas or fluid, and the questions of pulsations, obstructions, etc.

Formulae for Pipe Conductivity. Various formulae have been devised to determine the flow of gas in pipes, but the one commonly used *for low pressure* is Dr. Pole's formula.

$$Q = c\sqrt{\frac{d^5h}{sl}}$$

Q = quantity of gas in cubic feet per hour at atmospheric pressure.

c = a factor, which may vary from 1000 to 1400, but a fair average value for which is 1250. This factor is inserted for the purpose of allowing for condition of the interior pipe surface, obstructions, such as tar, etc.

d = diameter of pipe in inches.

h = differential head, or pressure, in inches of water.

s = specific gravity of gas, air being 1.

l = length of pipe in yards.

From this formula it appears that the capacity of a pipe to transmit gas under low-pressure conditions, among other factors, varies as the square root of the fifth power of the diameter. As a result of this it may be stated that when a pipe is doubled in diameter its capacity under low pressure is multiplied about 5.6 times.

For High Pressure. The following formula covers the range of high-pressure artificial gas:

$$Q = 33.3\sqrt{\frac{d^5(p_1^2 - p_2^2)}{Ls}}$$

Q = quantity of gas in cubic feet per hour at atmospheric pressure.
d = diameter of pipe in inches.
p_1 = *absolute* initial pressure in pounds per square inch.
p_2 = *absolute* terminal pressure in pounds per square inch.
L = length of pipe in miles.
s = specific gravity of gas, air being 1.

For Very High-Pressure and Long Pipe Lines. The formula for ordinary high-pressure work, previously given for use with artificial gas, is found to give results that are too small when applied to a higher range of pressure and long pipe lines. In particular, for natural-gas work, where pipe lines many miles in length are in use, it is found in practice that more satisfactory results are secured from the following formula:

$$Q = 42\,a\sqrt{\frac{p_1^2 - p_2^2}{L}}$$

Q = quantity of gas in cubic feet per hour at atmospheric pressure.
a = a factor, which in practice is found to vary with the diameter of the pipe, and for which fairly satisfactory amounts have been determined. For instance, $a = 95$ for a 6-inch pipe, 556 for a 12-inch, etc. See Ohio Geological Survey report.
p_1 = *absolute* initial pressure in pounds per square inch.
p_2 = *absolute* terminal pressure in pounds per square inch.
L = length of pipe in miles.

This last formula is based upon a gas of 0.6 specific gravity. Where the gravity of the gas varies the quantity found is multiplied by the square root of 0.6 divided by the gravity determined. Temperature corrections are usually neglected in natural-gas measurement.

Elevation. In the olden days the question of elevation was pertinent. Gas, being lighter than air, in a confined pipe tends to exercise greater pressure at higher elevation, as compared to the atmosphere, because it weighs less than the equivalent column of air under the condition of being exposed to atmospheric pressure at the initial low point, as, for instance, through a gas holder.

When gas was distributed entirely under low pressures some points of a given city lying much below the level of the works received insufficient pressure, and other points, much above the works, received excessive pressure.

Recently, however, where high pressure is used, the question of elevation causes no concern because of its comparatively slight ef-

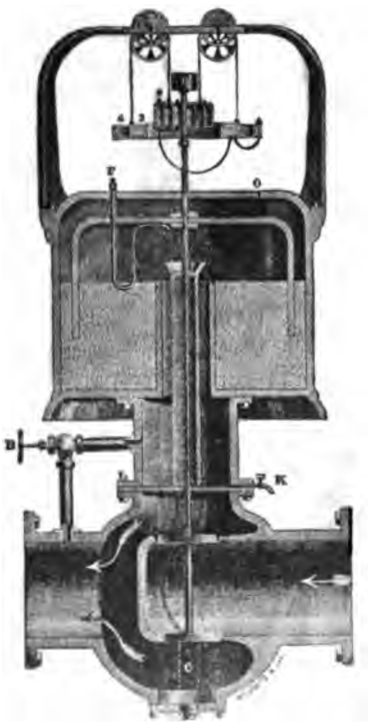


FIG. 19.—Station Governor.

fect under such conditions. Under low-pressure conditions, and with gas of about six-tenths specific gravity, the difference in pressure due to 100 feet elevation is about six-tenths inches water column.

Station Governor. A station governor is an apparatus which automatically maintains a given outlet pressure, which must be less than the inlet pressure. This is simply produced by the effect

of the outlet pressure on a float or a diaphragm. Some governors have been devised which increase or decrease the pressure automatically according to the demand.

Principles of Design of a Distribution System

We will first consider the principles underlying the design of a low-pressure distribution system.

Under this kind of a system we are limited to the maximum pressure allowable on consumers near the plant or holders, and by the minimum pressure allowable on the outlying consumers. For purposes of illustration, assume this maximum and minimum to be 6 and 2 inches, respectively. Then the maximum differential head is 3.8 inches, allowing 0.2 inches drop in services.

Next, having a complete map of the city, it is necessary to determine the maximum demand per unit of area, which for purposes of illustration we may assume as 1 square mile, and having selected the center of each square mile, we proceed to run low-pressure feeders from the works, in several directions if necessary, and large enough to furnish all the gas required at peak load to each unit of area reached by such main, and under the limitations of pressure assumed. If we determine that the loss of pressure from the center of each unit of area, to the outside limits thereof at peak load, shall not exceed 1 inch, then the maximum drop in pressure in the feeders from the holder outlets must not exceed 2.8 inches to come within our assumed limits.

On the basis of this assumption we are thereupon obliged to design the distribution system in each unit of area so that at peak load the maximum drop in pressure from the center, or point of supply from the feeder mains, to the farthest outlying point in each area shall not exceed 1 inch at peak load to come within our required assumed conditions.

To do all this requires the knowledge of maximum demand per consumer, the probable maximum number of consumers per block and per unit of area, the length of blocks, and certain other practical considerations, such as presence of electric surface-car line tracks, etc.

Naturally, smaller and simpler systems for smaller cities are easier to design, but the principle of maximum permissible drop in pressure is the same.

Design for High Pressure. When we come to consider high-pressure systems the same general principles hold true. We may run high-pressure feeders to the centers of the units of area, or we may design them to carry only moderate pressure, say up to 5, 6 or 8 pounds per square inch. If such a system is adopted, it becomes necessary to install pressure-reducing devices at the points where the high-pressure feeders deliver gas into the low-pressure system. Such devices are called district regulators.

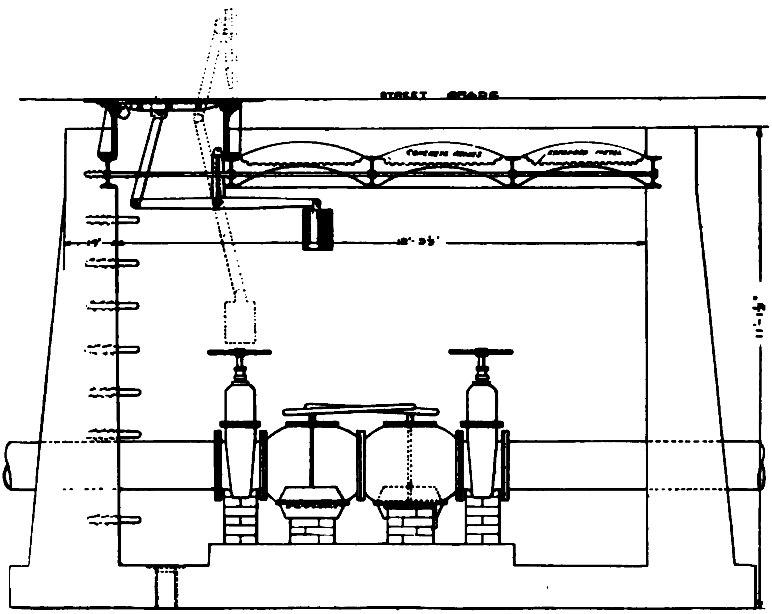


FIG. 20.—Section of Manhole on 5-lb. High-Pressure Line.

Another entirely different system is to carry moderate or high pressure on the entire system of mains. In such cases it is necessary to install pressure-reducing devices on each pipe entering each and every consumer's premises to reduce the main-pipe pressure, whatever it may be, to the pressure required by the consumer. Such devices are called individual gas-pressure regulators or governors.

The advantage of the use of high pressure lies in the fact that much smaller distributing pipes can be used, thus saving great investment charges. The cost of compressing gas is generally a small item.

Drainage of Mains. Artificial gas, as it leaves the works, always contains water vapor and various hydrocarbon vapors, which condense out of it as it passes through the distributing pipes, owing to changes of temperature and other causes. These vapors condense and liquefy, forming the so-called drip water. For this reason it is necessary to lay artificial gas pipes on a slight grade, and at the low points devices for collecting this drip water are installed so that it may be pumped out.

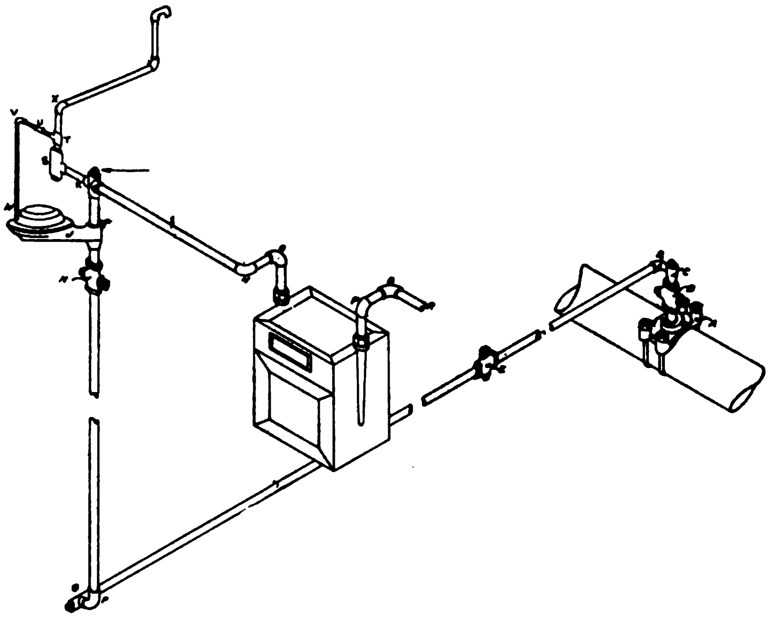


FIG. 21.—High-Pressure Main, Service Meter and Drip Installation.

A. ¾″ saddle with 5/16″ main top (galvanized).
B. ¾″ corporation cock with ½″ opening.
C. ¾″ street tee (galvanized).
D. ¾″ street ell (galvanized).
E. ¾″ curb cock with full gas way.
F. ¾″ street ell (galvanized).
G. ¾″ tee (galvanized).
H. ¾″ meter cock with 5/16″ gas way.
J. High-pressure governor (see schedule).
K. Cross.
L. 1′ ell.
M. 1′ vent from safety seal (end protected with No. 16 wire gauge).
N. ¾″ ell.
O. Reducing ell.
P. Reducing ell.
Q. 1″ ell.
R. To riser.
S. Mercury seal (see schedule).
T. 1″ x ⅜″ tee.
U. ⅜″ long screw.
V. ⅜″ ell.
W. ⅜″ vent from regulator.
X. 1″ ell.

Materials and Joints. For low-pressure distribution, and in the larger cities it is customary to use cast-iron for the main pipes on account of its long life, resistance to corrosion and to electrolytic action. The joints are almost universally of the bell and spigot type, in cast-iron mains, and the jointing material is either lead or cement, caulked or placed into the joint against an inside roll of jute packing to prevent it from entering the pipes.

Such joints are not conceded to be safe at high pressure, and when wrought-iron pipe is used screw or threaded joints are used.

On account of the mechanical strength of cast-iron, it is to-day the general practice to use but little pipe smaller than 4-inch cast-iron pipe for gas distribution, so that under that size wrought pipe is employed. Under 6-inch pipe the wrought is usually cheaper in first cost than cast-iron pipe. Pipes are usually much stronger than required to merely resist the internal pressure. External conditions, such as pressure of soil, loads, settlement, corrosion, etc., are the factors which determine the minimum permissible thickness of pipes.

Special types of pipes and joints have at various times been brought forth, such as Universal, vitrified clay, and even wood has been used, but to a very small extent.

Gas mains are usually laid deep enough to be under the frost line, and are kept away from car tracks and underground obstrucstructions as much as possible. Services, or the pipes leading from the mains to the consumers' premises wherever possible, are graded into the mains.

Electric surface-car lines have proved a bug-bear to underground piping systems on account of electrical current leakage setting up an electrolytic action. A portion of the return current from such car-line systems finds its way into the piping and leaves it again usually at some point near the generating or substations, or where it jumps to some other conductor. The troubles occur where the current leaves the pipes.

Various remedies have been suggested and tried, such as double systems of piping, one on each side of the car tracks, also various forms of insulated pipe covering and joints, also bonding the pipes to the rails or to the return conductors. All, so far, have proven to be more or less in the nature of palliatives and not complete remedies. The subject of electrolysis is one of great importance.

As I have used more than the time allotted me, I shall not take

up the subject of the gas meter, the instrument employed for measuring the amount of gas used by the consumer, or house piping or photometry, as I understand some of the subsequent lectures will incorporate about all there is to be said upon these subjects.

I would like to say a few words regarding calorimetry. Owing to the fact that by far the greater proportion of gas sold to-day is sold as a heating agent, either through fuel appliances or through mantle burners, it seems necessary to change our system of measuring quality to one that will define the calorific value. This may

FIG. 22.

be determined in two ways, first, from the chemical analysis gas, as the heating value of its constituents are pretty well known. There has been, however, adopted for quite general use an instrument whose essential principle of operation is, that the products of combustion of a gas shall be passed through a vessel which is water-jacketed, and in which the radiated heat from the flame and the sensible heat from these products of combustion are absorbed by water in the jacket. The quantities of gas and water being known, the rise in temperature furnishes a measure of the amount of heat liberated by the combustion of that amount of gas.

VII (2)

THE MANUFACTURE AND DISTRIBUTION OF ARTIFICIAL GAS, WITH SPECIAL REFERENCE TO LIGHTING

By Walter R. Addicks

Introduction

The subject of this lecture, "The Manufacture and Distribution of Artificial Gas, with special reference to Lighting", is so comprehensive that it is difficult to outline the field without slighting essential features of the gas business covered by the assigned subject.

The following sub-divisions are made to facilitate reference.

(A) Quality of Artificial Gas.

(B) Purity of Artificial Gas.

(C) Uses of Artificial Gas.

(D) Kinds of Artificial Gas (including Natural Gas for comparison).

(E) How Artificial Gas is manufactured.

(F) The handling, within the gas plant, of raw materials, of by-products, and of the finished product, Artificial Gas. The Retort Coal Gas Process described for illustration, with some reference to an auxiliary carburetted water gas plant useful for enriching coal gas, for utilizing the coke by-product of the Retort Coal Gas Plant, and caring for variation in the daily demand for gas.

(G) Distribution of gas from Storage Holder at Plant through transfer mains to the City Distribution Holder.

(H) Distribution of gas from Distribution Holder through Street Main System to the gas service pipes leading to the houses.

(I) Distribution of the gas from the Street Mains through gas service pipes, house service pipes, meters and governors to appliances for utilizing the gas.

(K) Observations relating to the piping of modern buildings and its relation to other utilities in use.

(L) Observations relating to the appliances used in burning gas.

(M) Influences that govern, in the selection of a particular type of gas, in a given geographic location.

(N) The future of the Artificial Gas business.

A. Quality of Artificial Gas

Gas should no longer be manufactured with special reference to lighting alone; it must still be designated by its candle power, where State laws, special and general, define quality as the candle power given by a specified quantity of gas burned through a flat flame or argand burner. The same quantity of gas burned by means of a bunsen burner as a heating flame in contact with the Welsbach mantle will give four times the light. It is quite common, in describing an artificial gas, to say that it is a 16, 18, or 20 candle power gas, meaning that when a specified quantity of gas is burned in a specified burner that it will give 16, 18, or 20 units of light when compared with the original unit of light, the candle.

B. Purity of Artificial Gas

It is required in many States that manufactured gas shall be free from sulphuretted hydrogen, and contain but limited quantities of ammonia and fixed sulphur. Such laws are quite unnecessary for the reason that the extending use of electricity will compel commercial purity in gas.

C. Uses of Artificial Gas

Artificial gas is used for:—

(1a) **Lighting** by means of the flat flame or argand burner.

(1b) **Lighting** by means of heat generated by the gas when burned in a Bunsen burner to a blue flame and making incandescent the fabric of the gas mantle.

(2) **Heating** through the use of the Bunsen flame in gas ranges for cooking, in a multitude of industrial appliances increasing day by day, and in steam boilers.

(3) **Power** by means of the internal combustion engine, made familiar to all by the introduction of the automobile.

D. Kinds of Artificial Gas (Including Natural Gas for comparison)

Artificial Gases are known as:—

(1) **Water Gas,** an odorless gas, containing Hydrogen and Carbonic Oxide, giving a non-luminous flame when ignited; is no longer distributed. It must not be confused with

(2) **Carburetted Water Gas** which is a mixture of water gas and oil gas having a distinct and pungent gas odor, and when burned gives a brilliant white flame.

(3) **Retort Coal Gas,** a gas of lower specific gravity and less brilliant flame than Carburetted Water Gas.

(4) **Coke Oven Gas,** similar in all respects to Retort Coal Gas; only 35% to 50% of the gas made is distributed, the portion distributed is usually of equal candle power to Retort Coal Gas. The remainder of the gas is burned under the ovens in place of coke.

(5) **Oil Gas,** a heavy petroleum gas which when burned in properly constructed burners gives a bright light. The California Oil Gas distributed on a large scale in California is a type of this gas. The familiar Pintsch Gas used in railroad passenger cars is a type of this gas: Blau Gas is another. Carburetted Water Gas contains from twenty-five to forty per cent of oil gas.

(6) **Acetylene Gas** gives a brilliant white light when properly burned. It is prepared as required by adding water to calcium carbide: the lamps of automobiles are a familiar example of its use. In country districts, hamlets, villages and small towns are supplied from a central plant with this gas.

(7) **Carburetted Air Gas.** This gas is the familiar type used in country houses and hotels; it is simply air saturated with vapors of gasolene.

(8) **Producer Gas** contains Nitrogen and about 25 per cent combustible gases; when cold usually requires heating to make it ignite; is seldom distributed beyond the boundaries of a manufacturing establishment.

(9) **Natural Gas,** one coming from the earth usually in a district where petroleum oil is also present, and frequently under pressure of many atmospheres; it is usually sold at much less cost than artificial gas so long as the natural gas supply remains available.

E. How Artificial Gas is Manufactured

(1) *Water Gas,* sometimes called blue gas, is made by raising the temperature of a fuel bed, by means of a forced blast of air, to incandescence (the Producer Gas made usually being wasted), when, the air being shut off, steam (H_2O) is passed through the fuel bed (C_2), which, on decomposing yields Hydrogen and Carbonic Oxide (CO), the Carbon being supplied by the fuel. Usually hard fuel is used, either anthracite coal or coke, though bituminous coal has been used. The fuel bed is usually contained in a cylindrical shaped fire brick furnace (Fig. 1 illustrates a twin generator) which in turn is surrounded by a gas pressure tight cylindrical steel rivetted

shell, supplied with gas tight stack valve, coaling and cleaning doors and proper air, steam and gas connections governed by valves, all manipulated by the gas maker. The cylinder containing this fuel bed is commonly called a Generator; when single it is eight to twelve feet in outside diameter and twelve to twenty feet in height. Water gas is colorless, odorless, specific gravity .550, yields on analysis (Stillman) CO_2 0.14, O_2 0.13, illuminants 0.0, CH_4 7.65, CO 37.97, H_2 49.32, N_2 4.79; on burning yields only a blue, non-luminous flame and 385 B. t. u. per cubic foot.

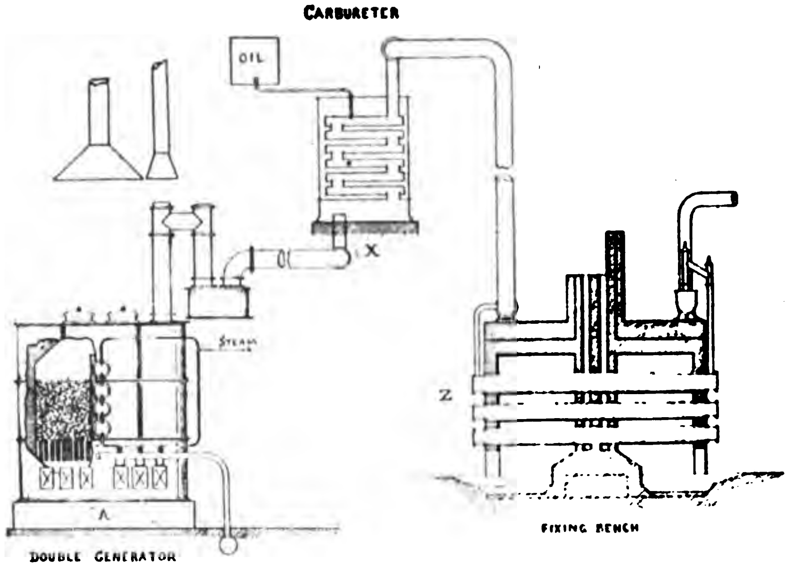


FIG. 1.

(2) *Carburetted Water Gas:* The water gas constituent of this gas is made in an identical manner as above outlined for water gas. The oil gas constituent may be made by heating oil in externally heated retorts, but is now usually made as follows: (2) The cylinder described for making water gas is connected with similar cylinders in duplicate or triplicate, though the diameter may be slightly varied and the height is frequently increased by fifty per cent. The additional cylinders are not used for containing fuel but are filled with many hundreds of standard fire brick placed in checker work fashion thus providing interstices between bricks for the passage of gases. The checker-brick work is raised to in-

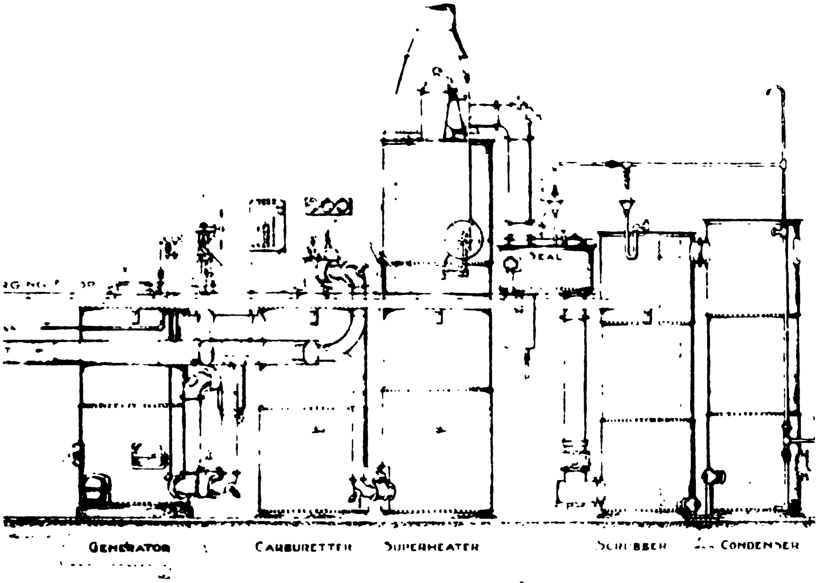

SEAL
GENERATOR
CARBURETTER
SUPERHEATER
SCRUBBER
CONDENSER

FIG. 2.

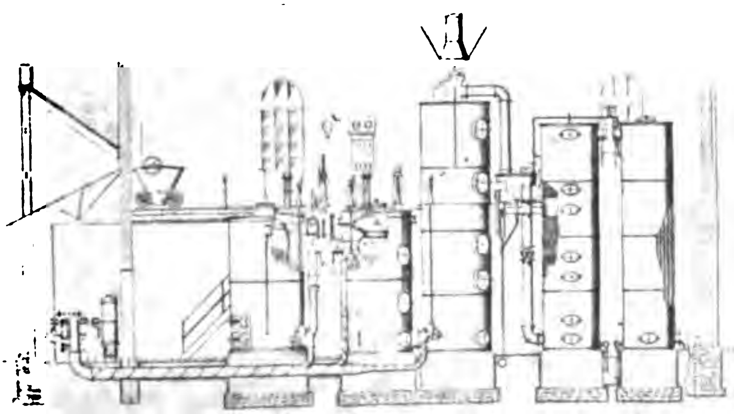
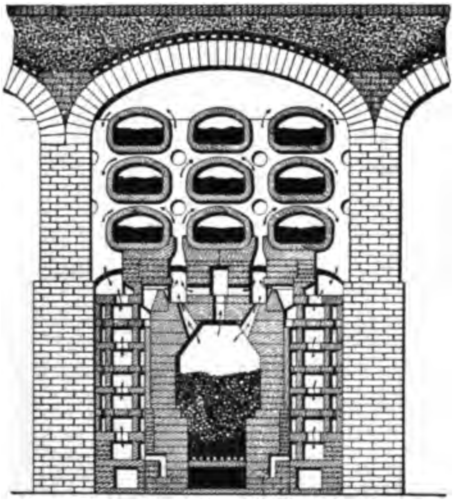


FIG. 3.

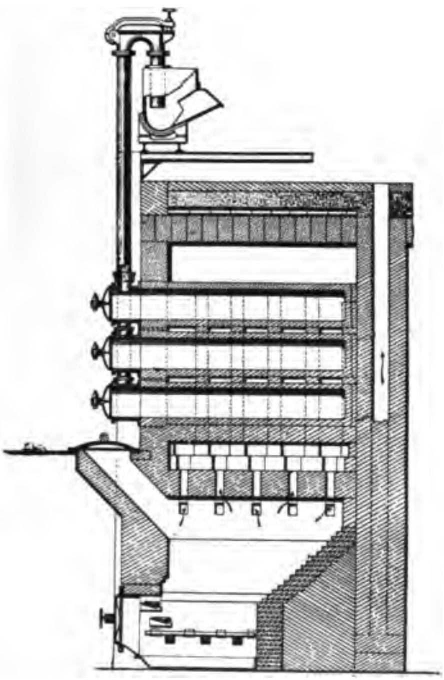
candescent heat by burning up the Producer Gas (wasted in the manufacture of water gas) made from the fuel bed of the Water Gas generator when it is being brought to incandescence by a blast of air preparatory to making water gas; all additional air required for this secondary combustion comes from the same source as for the first. When two additional cylinders are used the second is called the carbureter, because petroleum is dropped on the hot bricks in this cylinder and on vaporizing gives light-giving properties to the water or blue gas flowing over hot from the Generator,

FIG. 4.

while the third cylinder, usually taller than the carbureter, is called the Superheater or Fixing Chamber; the function of the hot fire brick in this cylinder being the further heating of the water gas-oil gas mixture and the "fixing" of the oil vapor products into fixed gas. This term fixed gas is used in a limited sense to include only usual atmospheric temperatures and pressures. (3) Carburetted Water Gas has the familiar pungent "gas" odor; it has a specific gravity of about .660, contains normally as sold, no sulphuretted hydrogen, no ammonia and but seven grains of sulphur compounds in 100 cubic feet. It yields on analysis approximately



Transverse Section Through Retorts.



Longitudinal Section Through Retorts.

FIG. 5.—Bench of Gas Retorts.

(Mass. State Inspector 1897) CO_2 2.91, O_2 0, Illuminants 14.92, Marsh Gas 25.90, CO 25.30, H_2 27.87, N_2 3.04. Ten thousand cubic feet of gas would require in its manufacture about 400 lbs. of fuel (where waste heat boilers are not placed after the carbureters) and 4½ gallons of oil; the gas produced would be about 25 candle power and as a by-product may yield from ¼ to 9/10 gallons of water gas tar.

(3) *Retort Coal Gas* is made by distilling at about 2200°-2600° Fahrenheit as much as 1000 lbs. of bituminous gas coal in a (4) clay retort having a "D" cross section typically 16 inches by 26 inches and 9 feet to 20 feet long, either vertically, inclined or horizontally placed. The dimensions as well as the position may vary and the weight of charge is graduated to the retort capacity; invariably the retorts are externally heated, (5) usually in groups of six to nine, by a single furnace but when retorts are 20 feet long, usually by two furnaces. Furnaces are usually fired without forced blast: The coke fuel is obtained hot from one of the group of retorts at the end of the distillation period, which varies from four to nine hours. About 10,000 cubic feet of gas of 16 to 18 c. p. is obtained from one gross ton of coal and there remains as by-products of manufacture, about 1000 lbs. of coke, about 12 gallons of tar, and ammonia sufficient to produce 20 to 22 pounds of sulphate of ammonia. Retort Coal Gas in all essentials has the odor of carburetted water gas, though the manufacturer may distinguish in the odor; it has a specific gravity of .400 to .450, and as distributed contains no sulphuretted hydrogen, though often 12 or more grains of sulphur compounds, 0.3 grains of ammonia, and on analysis yields approximately CO_2 1.75, O_2 0, Illuminants 4.88, Marsh Gas 33.90, CO 6.82, H_2 46.15, N_2 may at times be found as high as 6.50 though 1.5% may be considered a fairer percentage. The heat units approximate 600.

(4) (6) *Coke Oven Coal Gas* is manufactured by charging several tons of bituminous gas coal in the top of an elongated "D" oven 26″ wide, 72″ deep, and 30 feet long, and distilling it normally at a lower temperature than in the case of Retort Coal Gas but for periods varying from 24 hours to 36 hours. The heat for distillation is obtained by burning the poorer quality of gas which comes off after the first 10 to 12 hours and, after removing the ammonia and tar, is supplied to the exterior of the coke oven through pipes at low pressures; air for combustion is in some systems heated in regenerators by the waste combustion gases from the

ovens and is supplied to the ovens under moderate fan pressures or by the natural draft of tall stacks. This process is really not a gas making process but a coke making process, in which gas is but a by-product. 3½ gross tons of coal produces 5200 lbs. of Coke similar to Bee Hive Coke and as by-products, 10,000 cubic feet of gas

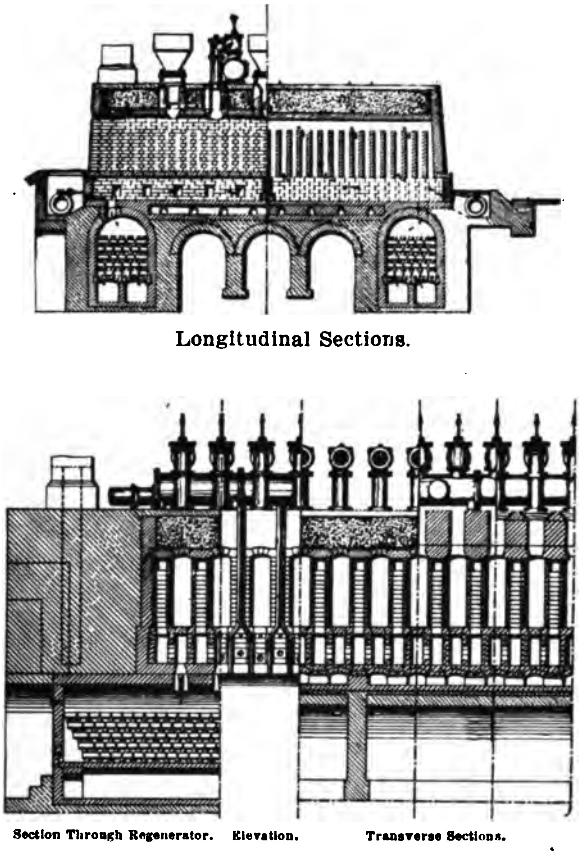


FIG. 6.—Early Type of Otto-Hoffman By-Product Coke-Oven.

of 17 to 19 candle power, 30 gallons of tar, and ammonia sufficient to manufacture 73 lbs. of sulphate of ammonia. The by-product gas available for distribution has a specific gravity and heat unit value quite similar to retort oven coal gas and yields on analysis approximately CO_2 0.1, O_2 0.1, Illuminants 5.55, Marsh Gas 38.90, CO 6.57 (may reach 8.00) H_2 42.1, N_2 6.65, and when made with

sulphurous coals, contains as impurities, after purification with lime for carbonic acid, foul lime for fixed sulphur compounds and oxide of iron for sulphuretted hydrogen, normally 18 or more grains of sulphur compounds and 0.2 grains of ammonia.

(5) *Oil Gas* may be made in iron retorts of similar pattern to the clay retorts used in Retort Coal Gas but they are smaller in cross section and usually not exceeding 9 feet in length: latterly clay retorts have been used. The external heating is effected by means of the best available fuel. As in Carburetted Water Gas the usual by-product is tar. Oil Gas burned in a special burner has a candle power of 60 to 100, specific gravity about that of air, and heat units of 1200 or over. (7) In California (see paper by E. C. Jones, American Gas Institute 1909, p. 410) Oil Gas is manufactured on a large scale and by the use of specially designed apparatus, in which oil is used for fuel to heat up checker brick work in chambers quite similar to the carbureter and superheater of the carburetted water gas apparatus, as well as to make the gas. The character of the oil gas here made is distinct from oil gas made in retorts and for a comprehensive description the student is referred to the able paper above referred to. The only residual, lamp black, is used in place of coal to manufacture water gas which is mixed with the oil gas. The low labor charge per thousand cubic feet made is an argument for the use of this type of gas where crude oil is very cheap. The analysis of the distributed gas is given as CO_2 3.63, Illuminants 9.70, O_2 0.34, CO 10.24, H_2 36.54, CH_4 33.16, N_2 6.39, Candle Power 21.88, B. t. u. 710.7 and specific gravity .523.

(6) *Acetylene* is made by adding water to Calcium Carbide (which has previously been made in the Willson (8) or similar Electric Furnace from lime and coke). When burned in special burners the resulting gas gives an intensely brilliant white light of about 250 candle power, has a specific gravity of .910 and a heat unit value of 756 B. t. u.

(7) *Carburetted Air Gas* (9) is made by forcing air through a carbureter in such a manner that it will pick up 10 to 17 per cent of gasolene vapor. It must be burned in special argand or mantle burners. Its heat unit value has been given as 815 B. t. u.

(8) *Producer Gas* is made in the Generator in the fuel heating period of Water Gas and Carburetted Water Gas manufacture. (10) It is likewise made by exhausting air or air and steam through any incandescent bed of fuel, or by means of a jet of steam below

Jones Oil Gas Set.

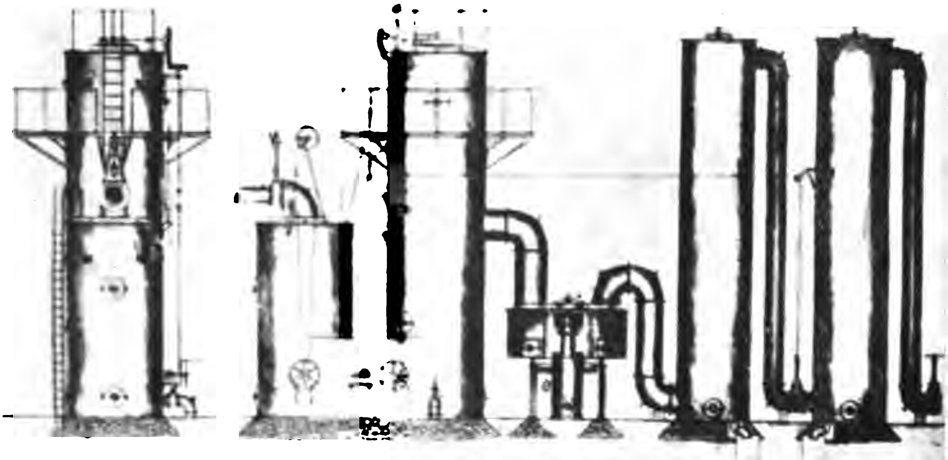


Fig. 7.

Fig. 8.

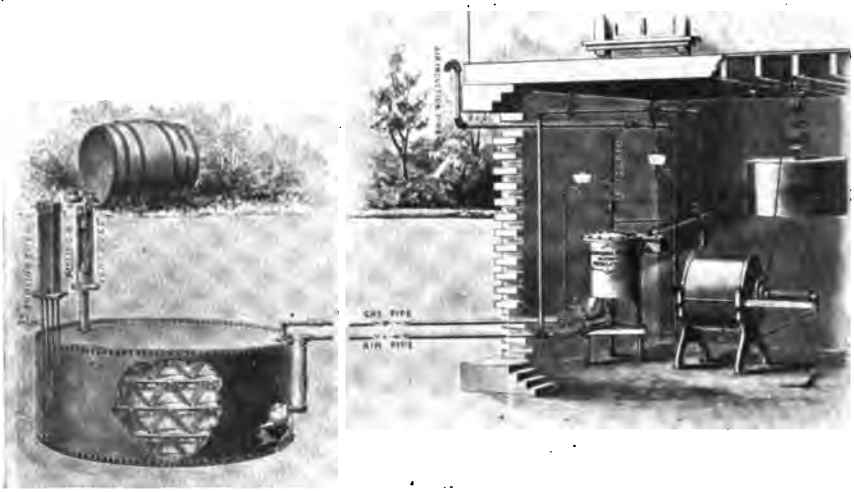


Fig. 9.

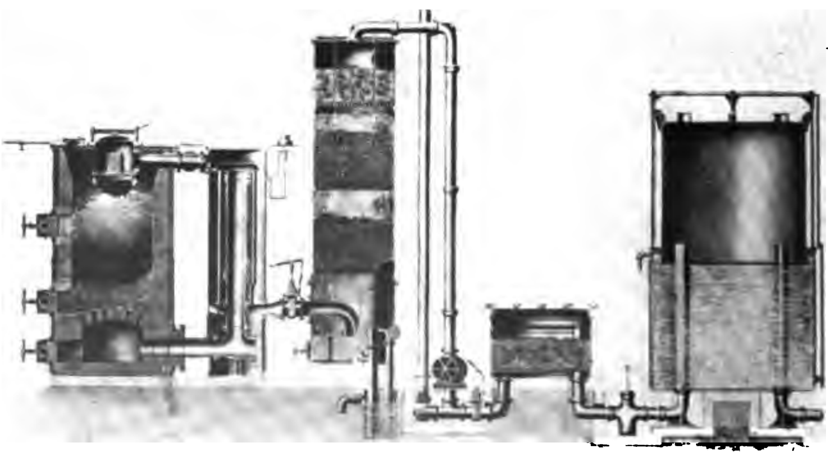


Fig. 10.

the ash pit injecting air and steam vapor through the fuel bed. This gas has a specific gravity of about .812 and heat units of 135-165 B. t. u.. Containing about 75% N_2 for maximum efficiency it should always be burned in its hot state as it emerges from the generator, as in the case of Carburetted Water Gas manufacture.

(9) *Natural Gas* has a specific gravity of .520 and heat units 1124. Analysis: CO_2 0.0, O_2 1.3, Illuminants 0.5, CH_4 95.2, CO 1.0, H_2 2.0, N_2 0.0. It issues from the earth in some localities at a pressure of from 300 to 400 lbs. per square inch. Its high heat units and low price per thousand cubic feet make it, for any purpose, a competitor that artificial gas cannot compete with on equal terms. Natural Gas is here mentioned to accentuate this fact and to give a fairly complete view of the commercial field occupied by gas.

F. Handling, Etc., Within the Gas Plant

The only raw material required to manufacture simple coal gas by the Retort Process (or the Coke Oven Process) is a coking bituminous gas coal. In general, a first-class bituminous gas coal should contain at least 36% volatile matter, no more than ¾ of one per cent of sulphur, and should be received in the condition that a ¾″ mesh screen at the mines would leave the larger portion of the run of mine coal. Natural conditions, handling, and cost of such a coal largely modify these general specifications.

Gas Coal to-day is mined (11a) by Electric Mining Machines, is transported (11b) by pit wagons to the mine coal tipples (11c) and dumped (11d) into hoppers with screens, and if a gas plant is favorably located cars loaded (11e) with screened coal at the mines may be run into the Gas Works coal storage shed, or even into the retort houses and there unloaded into the retort house coal bins. In other cases coal cars may go to tide water and the coal be discharged into (12) large capacity ocean going steamers that will deliver the coal alongside the gas plant wharf several hundred miles distant, or the coal cars may be carried hundreds of miles and then discharge into harbor lighters of about 1000 or more tons capacity which deliver the coal to gas plants five to forty miles distant. In the latter case the coal contained in the railroad cars from the mines may be dumped bodily or through chutes into the lighters without any hand labor. (13a-13b.) The Astoria (14a) coal gas plant will serve as an illustration of retort coal gas manufacture: On arrival at this gas plant (14b) automatic grab

FIG. 11a.

FIG. 11b.

FIG. 11c.

FIG. 11d.

buckets picking up two gross tons of coal at a trip deliver the coal. through the instrumentality of an electrically driven traveling crane, to either 50 ton railroad cars, that may be sent direct to the retort houses, or to temporary coal storage pile at a rate as great as 250 tons per hour per crane.

An electrically driven storage bridge 600 feet long (15) with a 7 gross ton automatic bucket transfers at the rate of 300 tons per hour, the coal from the temporary storage to the storage yard, or the unloading crane first mentioned may reclaim the coal from the temporary storage and place it in 50 ton cars for its journey to the

FIG. 11e.

retort house. The storage bridge at appropriate times transfers coal in storage to the same 50 ton cars, or when conveniently and happily located, may deliver the coal directly to the track hoppers in front of the retort house.

Ordinarily a 40 ton steam locomotive places two 50 ton cars containing different grades of coal side by side on two parallel surface railroad tracks at one end of the retort house; beneath the tracks is a hopper into which the cars are unloaded simultaneously at varying speeds. Usually one car contains a very sulphurous while the other contains a less sulphurous coal, and thus a uniform mixture of coals is obtained. The track hopper contains a chain scraper conveyor which moves the coal at the rate of 125 gross tons per hour

FIG. 12.

FIG. 13a.

up an inclined plane dropping it at the end into coal crushers, which discharge the coal uniformly crushed into vertical elevators which raise the coal to the roof of the retort house where the coal falls on to longitudinal conveyors, which in turn distribute the coal into longitudinal coal bins in the inclined retort house, and, with the aid of cross conveyors store it in large bins convenient for charging machines in the case of the horizontal retort house.

In the inclined house (16) the coal drops by gravity into measuring hoppers which are manipulated by hand and the coal thus directed to its final resting place by gravity into a "D" retort

FIG. 13b.

normally 16″ x 26″ x 20 feet long. In the horizontal house the coal drops into a charging machine electrically controlled (17) which is run on rails opposite to and below the level of all retort lids; this machine measures all charges and charges the retorts by means of large scoops driven into the gas retort, on releasing its charge of coal uniformly distributed in the retort the scoop is withdrawn.

While the charge remains in the retort which is heated on its exterior by the combustion of hot coke drawn from a previous charge, gas is being continually driven off through a seven inch ascension pipe as will be presently outlined. After a distillation period that may vary from 4 to even 8 or 9 hours, the mouthpieces are

FIG. 14a.

FIG. 14b.

FIG. 15.

FIG. 18.

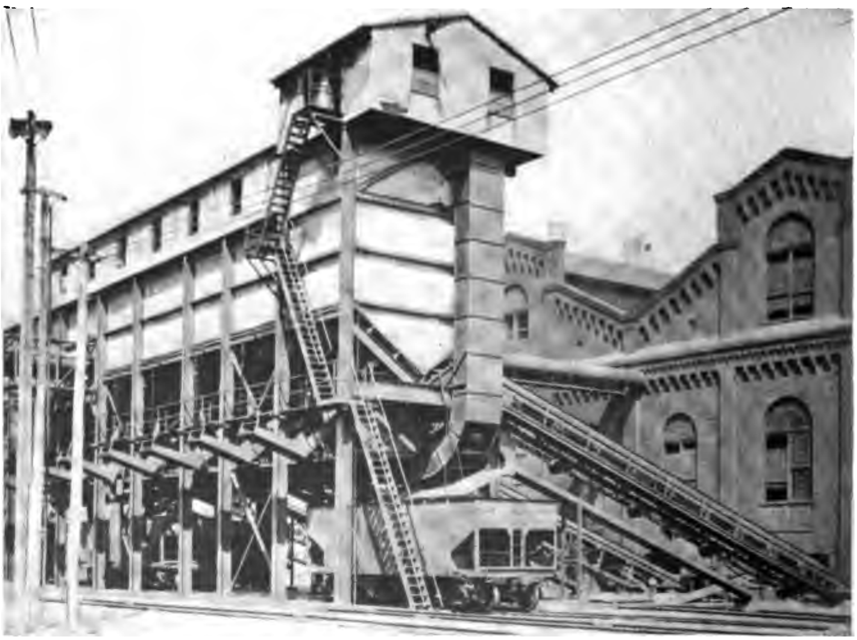


FIG. 19.

FIG. 20.

FIG. 21.

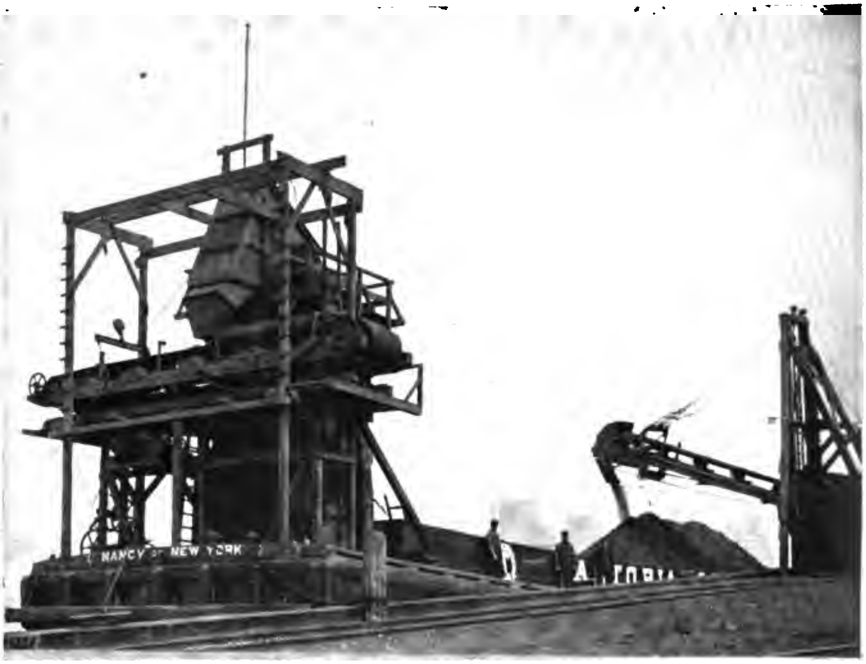


Fig. 22.

Fig. 23.

FIG. 24.

slacked off, fired and opened, and the residue of the coal being deprived of its volatile matter and now called coke, is either, in the case of an inclined retort, allowed, by gravity, to fall into a conveyor in front, or in the case of a horizontal retort, is pushed by an electrically controlled machine (18) somewhat similar in appearance to the charger, on to an electrically driven longitudinal hot coke conveyor running below the mouths of all retorts. Some of this hot coke may be deflected into the bench furnaces for heat-

FIG. 25.

ing the retorts externally, but the larger proportion proceeds along the house, meeting sprays of quenching water in its travel, and drops at the end of its journey into transfer bucket conveyors which convey it horizontally and vertically into a coke storage bin. (19) By gravity, coke is delivered from the storage bin (20) to 30 ton cars on a grade railroad and by means of 40 ton locomotives delivered over a track hopper (21) at the wharf. The coke falls to an electrically driven belt which delivers the coke (22) at a speed of 200 net tons per hour to a barge alongside. Up to this time all material has been handled by electrically driven mechan-

ism, except in the case of the steam locomotive and the hand manipulated measuring hoppers in the inclined retort house.

The barge is towed to the coke distributing points and by means of a belt conveyor within the barge located just over the keel, of a bucket elevator (23), and athwartship or cross belt conveyor in the bow (all driven by a single kerosene internal combustion engine) is delivered at the rate of 60 tons an hour on to an electrically driven inclined belt conveyor located on the wharf which (24) deposits the coke on a coke platform. From the platform it is delivered by gravity (25) over coke screens to teams or motor trucks which in turn deliver it into the sidewalk chutes of commercial buildings, apartment house steam plants or other users of coke. Only here, beyond the jurisdiction of the manufacturer of gas, is any hand labor applied since the coal left the pick of the miners in the mine from which it came. An exception to this statement would exist where coke has to be carried in baskets from the team on the street to the storage bins of the user.

A convenient auxiliary to Retort Coal Gas manufacture is a Carburetted Water Gas Plant. The fuel used to make the water gas is coke, and this should be delivered hot direct from the coal gas retorts but when necessary quenched coke is taken from the coke storage bins for use in the water gas generators in adjoining generator house. Detail explanation is omitted for want of time, the explanation of the manufacture of carburetted Water Gas heretofore made E1 and 2 being deemed sufficient.

As previously pointed out 1000 lbs. in coke from each 2240 lbs. of bituminous gas coal received at the coal wharf must be disposed of as a by-product in Retort Coal Gas manufacture; the great value of this primary by-product must be at once apparent.

While the coal lay in its hot bed in the retort the 36% volatile matter was seeking an outlet (26) via the ascension pipe before spoken of. The length of time the charge remains under distillation depends upon the degree and uniformity of heat, the character of the coal and the distribution of the charge in the retort, as well as the conductive qualities of the retort, for all have their influence on the resulting products. The heating of a charge of coal distills the volatile matter and causes a gas pressure within the retort; it is not desirable to have too great a pressure accumulate because of loss of gas through the porous sides of the clay retorts; the gas outlet of a retort or ascension pipe terminates in a metal chamber,

Fig. 26.

Fig. 27.

called a hydraulic main located above the retort bench; the ascension pipes are sealed in water originally but later by accumulations of hot tar and ammoniacal liquor, products formed from a portion of the 36% volatile matter in the coal that become liquid at the temperature of the gas on passing the water seal. To prevent excessive pressure within the retorts a gas pump called an exhauster

FIG. 28.

is installed in a house (27) beyond the retort house and the exhauster is run at a variable speed, by the aid of automatic governors, so that all the gas as driven off in the retorts is at once drawn away from the hydraulic main under a partial vacuum sufficient to overcome the water seal in the hydraulic main and to prevent but a very slight pressure in the retort.

Forty years ago cast iron retorts were in use in coal gas benches

FIG. 29.

FIG. 30.

FIG. 31.

and then no exhauster was thought necessary as gas could not penetrate in excessive quantities the cast iron retorts. In the Pintsch Oil Gas process cast iron retorts may still be used, but so far as I am aware, no coal gas works to-day employs their use. Frequently gas in traveling from the retort house to the exhauster house is cooled by atmospheric influences either in the pipes leading to the exhauster house or by specially designed apparatus. The

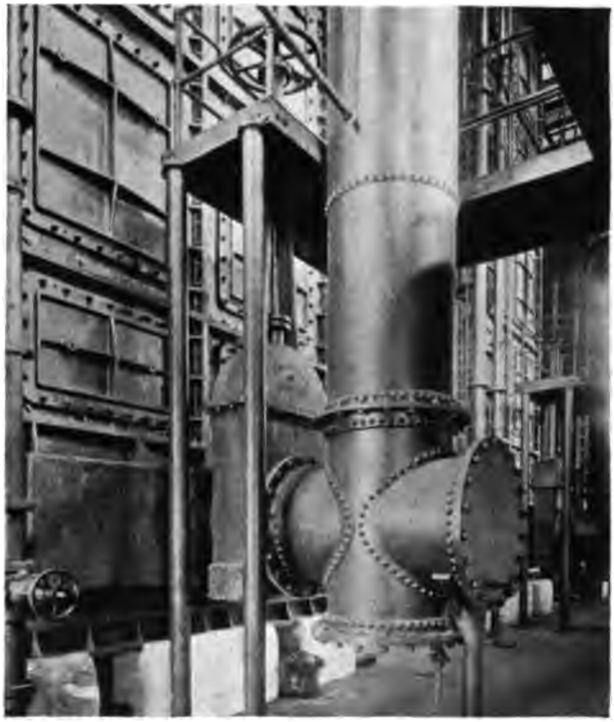


FIG. 32.

gas temperature at the inlet of the exhausters closely approximates 120° Fahrenheit.

On passing through the exhauster outlet the gas immediately is under pressure, for the exhauster is then forcing the gas to the storage holder against the storage holder pressure, which varies, depending upon its height, as will be explained later; additional pressure is produced by backpressure in overcoming the resistance of the gas travel through apparatus on the way to the holder as

well as by the skin friction of the main gas pipes of the system. Should the exhausters all stop simultaneously a safety gas blow out governor would allow the gas egress to the open air above the Exhauster house roof, thus preventing excessive accumulation of gas pressure between the exhausters and the retorts.

Raw gas from the exhausters passes first through (28) mechanical tar extractors having plates with small openings that break up the gas volume in small streams and by friction disengages tar from these gas streams; the raw gas next passes through horizontal rotary scrubbers (29) where hydrocarbon liquids extract the naphthalene in the gas. It is now believed that these washers should be placed next in order to the condensers later spoken of; from the naphthalene scrubbers the gas passes through a liquid solution of sulphate of iron in the (30) cyanogen washers which deprive the gas of any cyanogen contained. The liquid on saturation is sent to settling tanks, then to filter presses which form in a pressed cake a raw product called cyanogen sludge (31) which is shipped to the chemical factories; residue liquor from the filter presses is put through drying processes and converted into dry sulphate of ammonia, which is bagged and placed on the market for sale. After this purifying process the gas passes through the cast iron tubes of surface condensers: (32) the tubes are surrounded by salt water, where available, and the water current is arranged so that the stream of warm water leaving the condenser meets the warm gas entering the apparatus.

On leaving the condensers the gas passes through water in ammonia washers (33) quite similar in their design to the Cyanogen and Naphthalene Washers, and the gas having been freed of all tar, cyanogen and naphthalene, now surrenders its last trace of ammonia.

The tar from the hydraulic mains, the main pipe connections, exhausters, tar extractors and condensers is led into underground tar wells from whence it is pumped into shipping tanks near the wharf, from whence the chemical contractors take it to make the tar into pitch, dead oil, and various coal tar compounds.

The ammonia from the ammonia washers is sent to underground ammonia tanks, and together with ammoniacal liquor recovered from the hydraulic mains and other connections and apparatus where tar is present, is all transferred to ammoniacal liquor tanks near the wharf, from which the chemical contractors remove it and

FIG. 33.

FIG. 34.

obtain therefrom anhydrous ammonia, sulphate of ammonia and other ammonia products.

The gas leaving the ammonia scrubbers next passes into the purifying boxes now usually a dry process of purification. Boxes (34) 40 feet square and 8 feet deep are uniformly spread with oxide of iron, usually deposited on white pine shavings supplemented by iron borings. The layers vary in thickness in practice, being in some cases upwards of 42 inches thick. The gas is here deprived of sulphur which is in the form of sulphuretted hydrogen. Some fixed forms of sulphur are undoubtedly taken up from time to time in the journey of the gas from the hydraulic main to the outlet of the purifying house and unless a very sulphurous coal must be used, no lime purification is found necessary to meet a 20 grain legal provision. Where it is found necessary to use the latter it is not an extravagant statement to make that the increased cost of purification (more particularly in the case of Coke Oven Gas) may be ten times the cost of ordinary oxide purification. It has been found that in order to eliminate fixed sulphur compounds that all carbonic acid must first be removed from gas in one set of boxes then lime fouled from sulphuretted hydrogen will attack the fixed sulphur compounds in a second set of boxes, and finally a third set of oxide boxes must be used to remove any sulphuretted hydrogen that may be present. These three independent processes must be carried on in the purifying house, where but one is required when using fairly low sulphur coal. One of the three processes (the second in order) is exceedingly disagreeable to the employees of the gas company and to the neighbors as well. So little value is now attached to the requirements for fixed sulphur compounds that England, having passed through the regulating by law stage, now no longer demands any specified freedom of fixed sulphur in gas; New York only very lately passed laws respecting sulphur, merely imitating the laws of other places without reference to any necessity. Massachusetts in this respect is also moderating its position as regards sulphur in illuminating gas.

Having passed the purifying house the gas now goes through 16 foot station meters, (35a-35b) in which the measuring drums run in water; gas measurements are made as near 60° Fahrenheit as atmospheric conditions permit but the measurements are corrected to 60° Fahrenheit and 30 inches barometer in any event. Here I might state that unaccounted for gas, not leakage as fre-

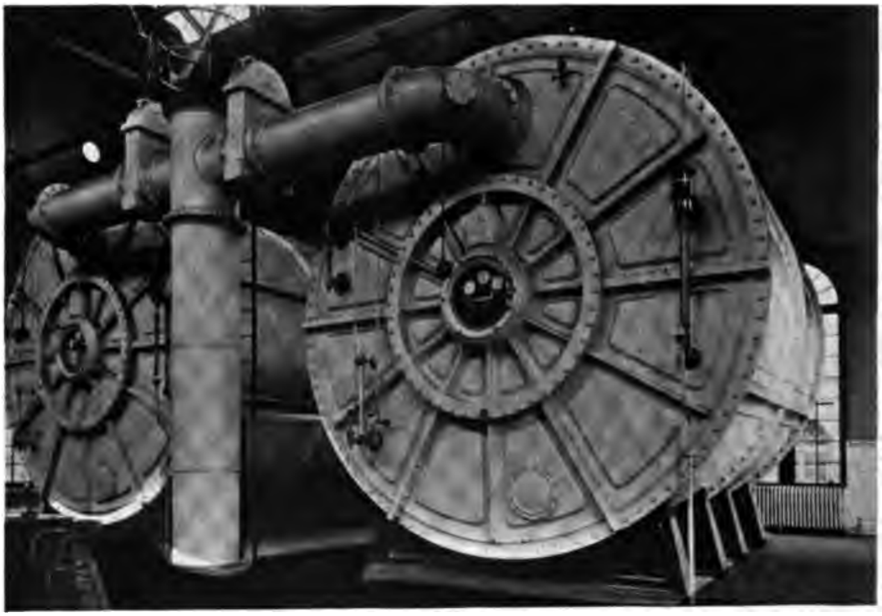


Fig. 35a.

Fig. 35b.

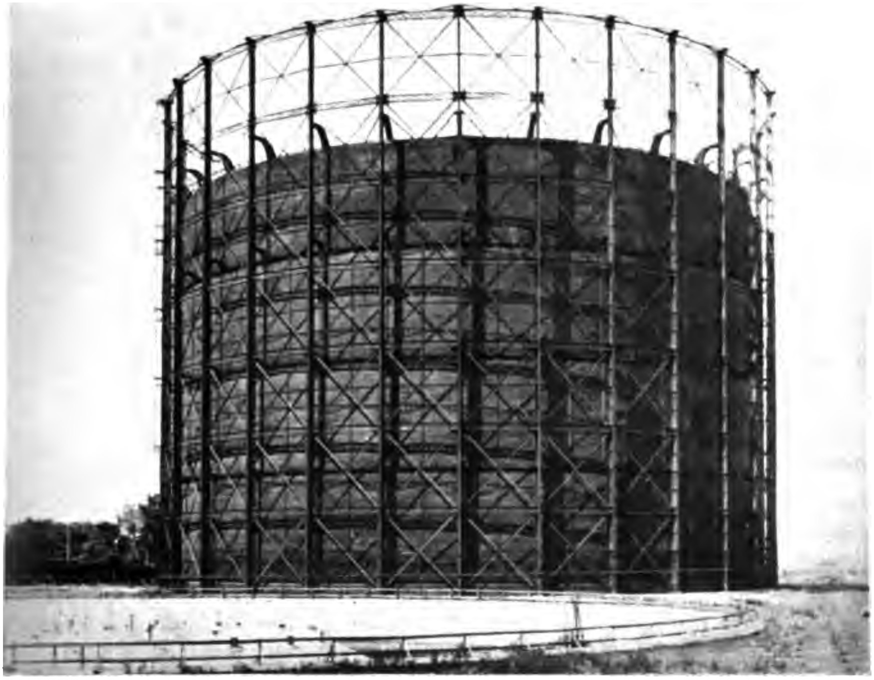


FIG. 36.

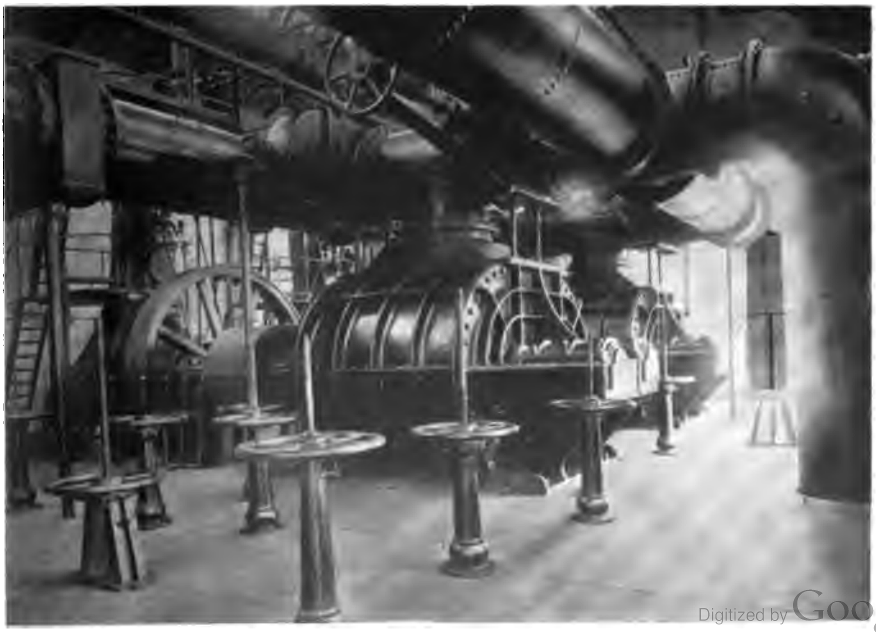
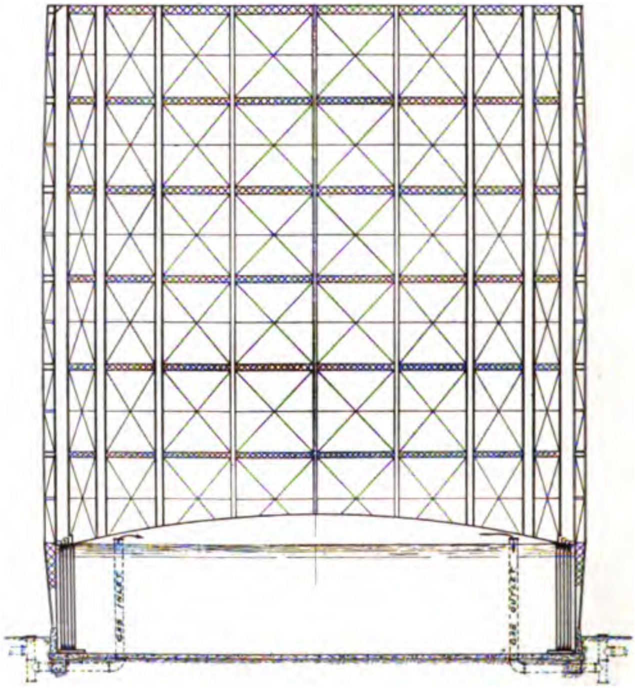


FIG. 37.

quently asserted, is ascertained by taking the sum of the readings of the station meters and subtracting therefrom the sum of the readings of all the consumers' meters, the remainder is unaccounted for gas, which includes actual loss of gas by leakage, loss of volume represented by difference of temperature at which the meters in



CROSS SECTION OF A GASHOLDER GROUNDED

FIG. 38a.

the cellars of houses measure their gas (which cannot be corrected) the slowness of the house meters, and condensation of hydrocarbons and aqueous vapor present in the gas itself.

Passing from the station meter the commercial gas now goes into the storage holder. (36) The largest holder in use holds 15,000,000 cubic feet; it is 300 feet in diameter and 233 feet high, having 48″ inlet and outlet pipes. The illustration shows an empty tank prepared to receive a second holder.

G. Distribution of Gas from Storage Holder to City Distribution Holder

In small plants the works' holder distributes the gas direct to consumers while in large plants Exhausters (in this service sometimes termed boosters or Gas Pushers) (37) pump the gas from the

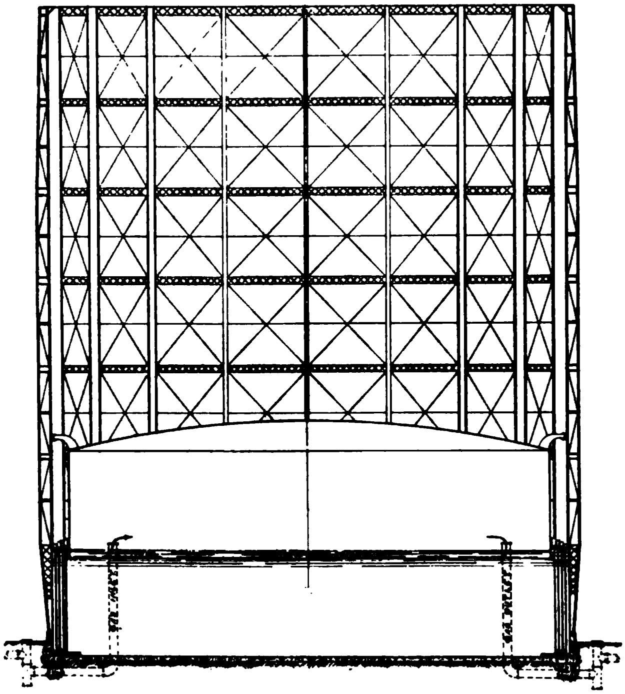
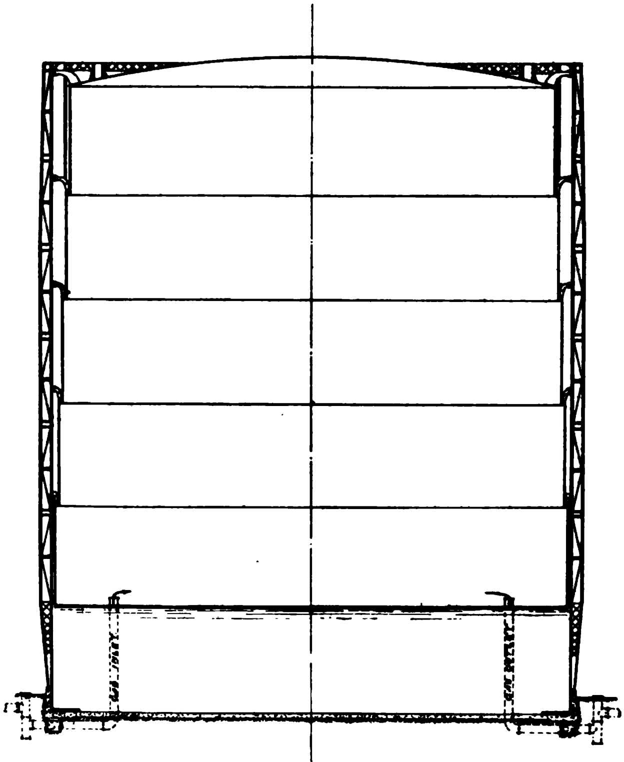


FIG. 38b.

works' storage holder into transfer mains, as large as 60 inches in diameter, and some times through tunnels under rivers into district Distributing Gas Holders.

It might be well to here call your attention to the method of obtaining the initial gas pressure used in gas distribution. It has been stated that the gas exhauster withdraws the gas from the retorts as rapidly as made and that after the gas passes through the exhauster it is under pressure due to the skin friction of pipes,

the resistance to the passage of gas through the apparatus described and the pressure of the gas storage holder due to its weight. In the case of the district holder, identical in all respects to the works' storage holder, the motive power (steam, gas or electric) driving a gas exhauster fills the holder and when gas has been forced into the holder the holder itself maintains the initial gas pressure on the supply mains in the following manner.



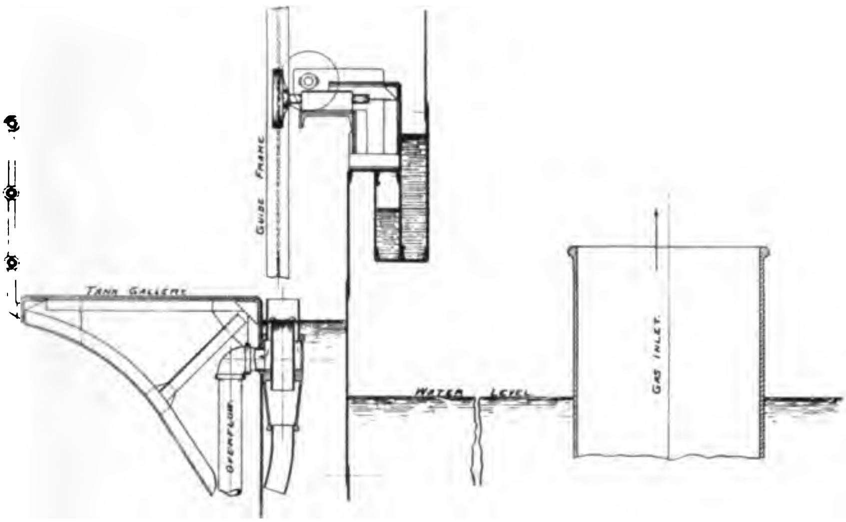
HOLDER FULLY INFLATED.

FIG. 39.

The gas holder is free to move vertically and when being filled is held in its vertical position by guide wheels rolling on guide framing supported and bolted to the tank wall. The top of the holder prevents the escape of gas upward, the cylindrical barrel or sides of the holder prevent any escape from the sides and the water in the holder tank prevents escape downward; the only man-

ner that gas reaches the holder or escapes from it is by way of pipes passing through the water of the tank; gas flow is governed by valves on these pipes in the valve house. The gas is in fact supporting the gas holder and the weight and area of the gas holder determines the initial gas pressure obtainable.

It would be quite impossible to have a water tank as deep as the gas holders in our large cities are in height, which would be necessary if the gas holders were not made telescopic. The photograph shows (a) a (38a) cross section of a gas holder; grounded, in such



DETAILED CROSS SECTION
SHOWING THE HYDRAULIC SEAL BETWEEN TWO OUTER SECTIONS

FIG. 40.

position giving no pressure whatever; (b) (38b) the holder proper just engaging an additional telescopic section; (c) (39) the gas holder entirely inflated with the first section or holder proper and its 4 additional telescopic sections filled. In the case illustrated the holder is 190′ 10″ in diameter, 230′ high and weighs 2,170,203 lbs. The holder proper or first section will give an initial gas pressure measured at the crown of the holder, of 4.9 inches of water (you remember that 27.68 inches of water is equal to 1 lb. pressure per square inch) the second section when added increases the pressure by 2.8 inches and gives a total of 7.7 inches—the third a total of 10.4 inches—the fourth a total of 12.5 inches—and the holder

fully inflated a total of 15.0 inches (if the holder were filled with air the air pressure would be 16.3 inches, the difference 1.3 inches is equivalent to a weight of 173,200 lbs. When the holder is grounded the water level in the tank is level, when the holder proper or first section is raised the water outside the holder is 4.9 inches out of level with the interior and when the holder is entirely inflated (40) the difference in level is proportionately increased. The inlet and outlet pipes should be higher in level than the tank walls and the tank overflow always above the level sufficient to permit the maximum alteration in water level without wasting water. While the water visible within the tank rises very perceptibly the original water level within the holder is but slightly altered because of the great difference of the water areas involved. The gas cannot escape from the telescopic joints because of water seals between the sections. When it is necessary to ground a holder and cut it off from the pipe system by valves, changes in barometric pressure or temperature would make the crown of the holder collapse, unless an opening to the atmosphere were made.

If the maximum initial gas pressure required does not exceed the gas pressure given by the holder proper or first section, then all the gas can be sent out of the holder. If a higher pressure than this is demanded then the gas exhauster must be called upon to supply the deficiency, for the holder cannot always be kept fully inflated, or its value would be lost.

I have taken some time to describe the gas holder, but it is the one feature of the gas business that is the envy of our electric brothers. What royalty would not an electric company pay for an equivalent electric device that would at an equal annual cost store, without loss, the latent energy of all their boiler and engine plant run for 24 hours, always ready at any second for maximum or unusual demand, and needing but the turn of a wheel or the automatic adjustment of a switch to bring its latent energy into action. The gas industry could not be what it is without the gas holder and without the aid of the hydraulic seal, as both are essential to gas manufacture and distribution.

H. Distribution Holders to Services

The gas in the District Distributing Holders passes into a Valve House (41) where valve men may control the initial pressure and hence the rate of gas flow through the various large street mains

20″ to 30″ or more in diameter which are connected later with a multitude of smaller street mains ranging from 4″ to 16″ in diameter. In special cases Gas Pushers are used to force the gas through the large mains for long distances before the gas is permitted to find its way into the smaller mains. The gas pressure to a district is regulated either by a gas regulator or by a valve man adjusting an ordinary gate valve. The valve man regulates the gas flow by watching the pressure of the gas leaving the valve house but in

FIG. 41.

some cases is assisted by the use of an ingenious electrical device which, on pressing a contact key, rings a bell whose strokes indicate the pressure in the mains a mile or more away; in such a case the valve man maintains a given pressure at that distant point quite independent of what pressure the gas is under on leaving the Valve House. The best the gas manager can do is to strive to furnish a given locality with uniform pressure—the exact amount, within reasonable limits, is not so important. It is impossible to give a uniform pressure of gas everywhere in

a gas system, for in order to distribute gas at all, difference in pressure must be established before the gas will flow in the pipes. Water distribution requires a pressure obtained by the use of reservoirs, stand pipes, or pumps in order to make it flow through a city system. The water pressure of a city system is not uniform any more than the gas pressure in a gas system.

In suburban districts the Gas Pusher is used to send gas many miles through small mains under so called high pressure; in this case we speak of the Gas Pusher as a Gas Compressor (it is usually of the piston type). At appropriate points in the system a branch pipe supplies a district through a reducing valve (usually in duplicate) into the local district system; the gas pressure maintained in such a district is the pressure that the district gas holder would furnish in ordinary circumstances; in fact a gas holder is frequently primarily supplied by a high pressure main in which case the high pressure main is really a transfer main similar to that heretofore spoken of, only the diameter is small and the gas pressure carried is greater. In some cases gas is supplied directly from a high pressure main to a house en route; in such a case a gas pressure reducing valve is placed in the house, but a safety seal is also provided, so that if the reducing valve mechanism fails to perform its work, excess gas pressure cannot come on the house meter or house fixtures, but the gas seeks a safe course to the atmosphere above the top of the house by means of an escape pipe.

The pressure carried in gas pipes in the street is quite independent of the strength of the gas pipe itself with respect to bursting by internal pressure. Any gas pipe would stand several hundred times the pressure it is subjected to in the ordinary district distribution of gas.

The danger of fracture of gas pipes comes entirely from the character of the soil and the use of the streets by other public utilities—electrical conduits, sewers, water pipes, steam pipes, conduits for telephone and telegraph and the like. During the installation and repair of these public utilities and following these processes the conditions underground are indefinite and complex. When a fault does develop in a gas main, the gas manager must have at hand emergency forces for instant service and it is not wise to give these men the task of coping with this useful servant under too high pressure, less it become a dangerous foe. Opinions may differ on the subject of gas pressures appropriate to use in public streets,

and fixed opinions are sometimes modified by extended experience—so that on this subject we can fairly say that "circumstances alter cases".

It is often suggested that the proper method of distributing gas, water, electricity, telephone service, steam and provide for sewage should be by installing all the conduits furnishing these in sub-surface chambers called pipe galleries (42) constructed the length and breadth of a town or city. The failure of many an untried but promising process is due to not taking into consideration all natural

FIG. 42.

influences and forces. Nature never fails to supply them all though even thoughtful and experienced men sometimes forget to take them all into consideration.

Time does not permit discussion of the pros and cons of pipe galleries, but the writer is opposed to their use, and believes that the pipe gallery cure is worse than the pavement disturbing disease. Corporations using the public thoroughfares should be required to restore the street surface disturbed to as good a physical condition as they found it. Under present conditions the maintenance and repair of the conduits of public utilities is conducted with a minimum of danger to the public; before advocating pipe galleries the possibilities of wide spread disaster should be first overcome.

I. Distribution of Gas from Street Mains to Appliances for Burning Gas

Usually gas mains are drilled and tapped with standard pipe thread and gas services, usually the smaller sizes of wrought iron or steel pipes, by the aid of proper fittings conduct the gas to within the foundation wall of the consumers' premises.* It is good practice to install a gas service in a straight line from the street main with a constantly rising grade to the house, provide at the street

FIG. 43.

main for reasonable settlement of street main, service or the soil supporting them, and provide a small sized opening within the house for access to the interior of the service pipe. Should the service pipe be exposed to atmospheric influences, as in the case of areaways in the front of the building, special precautions are advisable where the winter temperature may be expected to be very low. Artificial gas has in suspension aqueous vapors and vapors of hydrocarbon, which may be liquefied at low temperature. It is advantageous to have these liquids flow back to the street mains

and collect into drips, which are chambers left in the street mains below the lower level of the mains. All gas mains in the street are very carefully laid on ascending and descending grades with drips installed at the low points. The drips are pumped dry from the street surfaces (43) by the use of a pump and receiving tank usually drawn through the streets by horses.

Any condensation of the hydrocarbon vapors deprive the gas of both its illuminating power and its heat unit value and is always

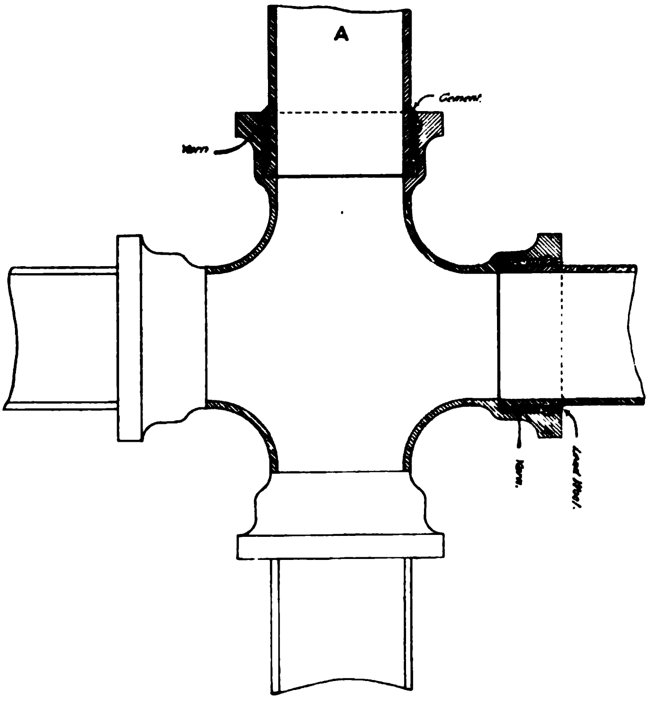


FIG. 44.

provided against so far as possible. The aqueous vapor in severely cold weather may be congealed and thereby gradually reduce the capacity of the service pipe below the requirements of service.

Naphthalene, usually in the fall season, sometimes gives trouble by obstructing the service pipes in a gas system. When the service pipe passes through an open area way the size is often increased, and the pipe is sometimes covered in some way, more particularly where entering the walls; this mitigates and sometimes eradi-

cates trouble with stoppages. It is wise to provide ample sizes of pipes for services dependent upon the gas demand. Some services are installed as large as the smaller sizes of street mains; in such cases the service pipes are connected with the street main in the same manner in which street mains are connected with each other (44) at intersections of streets, usually with lead or cement joints. Service pipes are frequently provided with cut-off valves located between the street main and the building supplied; when so placed they should be of a type not apt to be inoperative through very infrequent use. The pipe leading from the street service to the gas meter is frequently spoken of as the inside or house service and its location and installation is dependent upon the needs of the service and the will of the architect or owner.

The gas meter in reality is a motor operated by the gas pressure originating at the gas holder but operating only when any gas outlet beyond the meter is opened to the atmosphere. Meters with drums revolving in water have gone out of use because of the difficulty of keeping the water level intact and from freezing troubles. Dry meters, so called, are almost universally used.

The essential parts of a typical dry meter are two main chambers, one on each side of a central gas-tight partition; each chamber is fitted with a hollow collapsible bellows or piston formed by a flat disc connected with the central partition by a gas tight cylindrical leather diaphragm, each piston being inflated and deflated within its own chamber and in rythm with its twin in the adjoining chamber beyond the central gas tight partition. The space within each piston and the chamber surrounding it are filled with gas and are independently connected by valve passages to a slide valve, usually of the familiar " D " pattern met with in simple steam engine practice, operating in a gas tight chamber at the top of the meter. The mechanism is so connected that in reality the meter is a double acting motor. The gas is measured by counting on a dial located in the front of the meter the volumes corresponding with the number of times the collapsible pistons are inflated and deflated. If a piston is deflated the disc is close to the central gas tight partition and as it expands it dispels its external volume in gas from the chamber surrounding it. When it is deflated the volume of gas within it is dispelled. Before installing a meter the volume dispelled by these pistons is carefully calibrated by means (45) of a small gas holder, whose capacity

is known by comparing its volume with that of a cubic foot bottle the accuracy of which is certified originally by the Federal authorities in Washington. If on test the dial mechanism of a gas meter indicates a measurement not within one per cent of the true volume, an adjusting device within the meter provides for correction that will produce a final result within that accuracy.

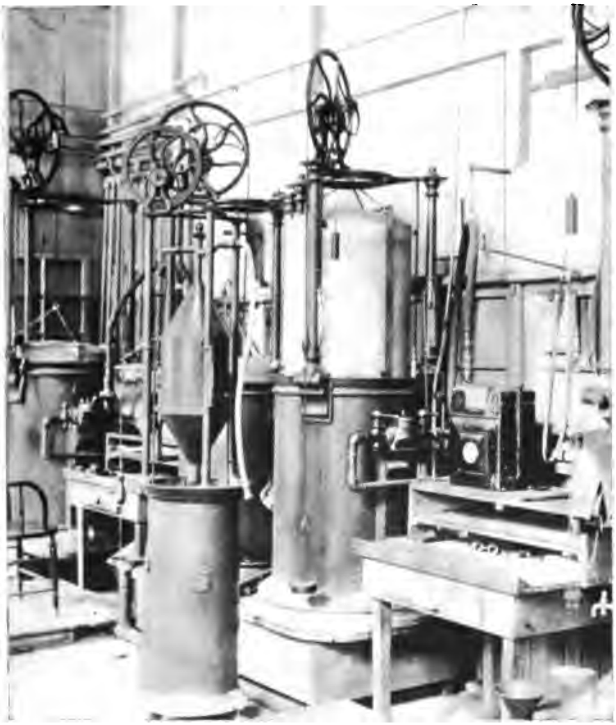


FIG. 45.

By custom and sometimes by law a gas meter (when tested on complaint for inaccuracy) is said to be correct or accurate if it measures within 2% of absolute accuracy, and it is a safe statement to make that the public buys no commodity, wet or dry, that so closely meets the requirements of absolute accuracy as in the purchase of gas.

Meters in use are subject to derangement but, fortunately for the consumer, they are more apt to become slow (that is, the dial

does not indicate the total volume of gas passing through the meter) than fast. Gas managers who do not consistently maintain the accuracy of the consumers' meters will find that their unaccounted for gas will become larger. The certificate of a public authority as to the accuracy of the meter set by a gas company is a satisfaction to the consumer, but no well managed gas company requires such inspection as a spur to the maintenance of their accuracy, for the interests of the stockholders, whether private or municipal has always demanded careful supervision of this important department. Gas meters are read when possible on the same date of each succeeding month, and bills are thus rendered for similar periods, which furnishes a basis for careful comparison. All consumers should learn to read their meters themselves; by so doing unnecessary waste in their use of gas is stopped. In a community where one apartment may be occupied by several tenants during a period of one year, or where the consumer cannot pay the necessary deposit required by gas companies, it has been found desirable to install prepayment gas meters. These meters are the same as other meters so far as gas measurements are concerned. There is a mechanical contrivance added that permits only that quantity of gas to pass the meter that is in value equal to a coin that is passed into the coin box by the consumer. As the last of this quantity of gas is passing the meter the valve mechanism reduces the outlet area which reducing the size of the gas flame warns the consumer that an additional coin is required in the money box. The coin attachment added to the ordinary meter largely increases the cost of the gas meter, and the coin collector must be added to the staff of the gas company. The readings and accounts of the prepayment meters must be kept in the same manner as the ordinary meters. Prepayment meters should only be installed in locations convenient for immediate access and where the consumer only has control.

Beyond the gas meter some consumers install a small gas governor; gas governors have their place but in practice when injudiciously installed they are of little value. As stated before the gas manager endeavors to furnish uniform pressure in a given locality. Where this is impossible a gas governor may be profitably used by the consumer. For photometrical or other delicate scientific work where absolutely uniform pressure is imperative their use is necessary. Gas pressure increases as the height of a building

increases, due to the difference in specific gravity of gas when compared with air; in tall buildings a gas governor in the basement cannot serve uniform pressure throughout the whole building. The increase in the pressure of coal gas may be roughly stated for example as one inch in a difference in height of one hundred feet; because of this fact it is customary to locate the gas holder at the lowest point in a district to be supplied.

For lighting (46) the most common method of burning gas is by the use of the ordinary metal or lava tip from which the gas on issuing and igniting first heats the carbon particles therein to incandescence before they are totally consumed. These burners are the batswing burner in which the gas issuing from a narrow slot

Fig. 46.

forms a thin sheet of flame; the fishtail in which two circular streams of gas coming in contact with each other spread out on ignition in a similar sheet of flame, and the argand burner where a series of small cylindrical jets issue from a multiplicity of openings arranged in a circle forming a cylinder of flame enclosed by a glass chimney, and air for combustion is supplied from the bottom of the burner. These burners may be expected to give from three to five candle power per cubic foot of gas burned depending upon the quality of the gas used.

The gas mantle (47) burner is displacing all other methods of burning gas for illumination. In this burner a partial mixture of air and gas is effected before the gas issues from the burner, and together with the air present at the burner outlet immediately affects complete combustion of the gas in a blue flame cone, which

coming in contact with the gas mantle renders it incandescent. Such mantles are either upright or inverted as the case may be; the candle power per foot of gas is five times that of a flat flame burner, but the mantles must be of good quality and properly adjusted and maintained to give these results. It is for this reason that many gas managers are endeavoring to maintain mantle burners for as low a price as possible to cover the cost of this work. In nearly all other appliances using gas it is burned to a blue flame as in the case of the mantle burner, and it is this fact that is tending to make a candle power requirement for gas obsolete,

FIG. 47.

for where a blue flame is required only the heat units in the gas are of importance. A dual standard is illogical and impracticable for it is a fact that candle power and heat units do not rise and fall in direct proportion even in the same kind of gas, and there is a wide difference in the heat units in different gases of the same candle power as measured by the flat flame or the argand burner. The kitchen gas range burners all use blue flame, many gas heating appliances likewise, though some radiator types of heaters use a flat flame burner. Gas logs usually use no primary air for the reason that some light is desirable to simulate a genuine wood fire. Gas to-day is used in many more ways for heating than for lighting, and it has been asserted that more gas is used to-day for heating and manufacturing than for lighting; it is a fact that the proportion of gas used in daylight hours is on the increase.

K. Piping of Buildings, Etc.

Before the era of high buildings, and the advent of a cheap and certain supply of electricity it never occurred to the architect to leave gas piping out of buildings, but it is not uncommon to-day—and the tenedency is acquiesced in by our electric brethren. The piping and wiring of a ten or twenty story building for water, toilet, sprinkler system, steam heat, refrigeration, electricity, telephone and gas is a work of no small proportions and a great expense. The natural impulse is to consider what can be dispensed with, and two methods of illumination being now seemingly unnecessary, gas pipes are being omitted where possible. In commercial buildings main risers are installed for the use of gas emergency hall lighting and for manufacturing purposes and in large apartment buildings for cooking and heating and emergency hall lighting. Many thousand dollars are thus saved the builder and owner. The consumer is then cut off from a choice of central station illuminant in so far as gas and electricity is concerned, though strange to say oil lamps are still in use even where both gas and electricity are available, and candles are also used in great numbers. It is a mistake to leave gas piping out of buildings, but it is unnecessary to pipe the large buildings so thoroughly as would needs be if electricity were not available. Buildings which have a private electric plant should always be piped for gas for lighting purposes, for it is frequently needed.

The modern builder to save the last dollar of construction cost desires to save all the steel possible by having the dead floor weight as small as possible and hence cinders with and without concrete are used above tile or brick arches. The pipes are sometimes embedded in the cinders and concrete. In course of time the sulphur in the cinders attacks the iron of the pipes laid in the cinders, and cases are many where entire piping systems have had to be abandoned because of the pipes becoming unserviceable. This deterioration in pipes is not confined to those used to conduct gas. When this system is used all pipes should be exposed or protected from possible corrosion.

In a building in New York there has been adopted a method of making the gas lighting and gas heating interdependent. The building is lighted by gas, its heat is utilized for the heating and when the weather is cold thermostats installed on each floor open valves on radiators which thereby diminishing by radiation the

steam pressure coming from a gas heating boiler in the basement causes a valve actuated by steam pressure to admit more gas to the gas burners furnishing heat to the heating surfaces of the boiler, thus supplying to the floor requiring it additional heat. Shutting off all light would still further increase the gas burned under the boiler, while increasing the gas light would automatically decrease the gas used under the boiler. This building is ventilated thoroughly with the exhaust fans used in the modern systems of building ventilation. The results are satisfactory at this writing. The gradual extended use of mantle lighting tends to a return of the former general practice of piping buildings for gas whether electricity is used or not. It is well that this is so. The writer believes that all buildings should be thoroughly piped for the use of gas.

L. Appliances Used for Burning Gas

This subject is rather beyond the limits of this paper and I will content myself with the enumeration of the uses of gas as follows:

For Lighting—By flat flame, argand and gas mantle burners, and through the agency of the gas engine, electric lighting is available.

For Household Use (48a) Cooking, heating, gas ironing, hot water heating and heat for many small appliances, such as coffee pots, chafing dishes, hot water kettles, curling irons, etc.

For Commercial Uses Hot water, instantaneous and automatic (48b), hotel ranges, broilers, caldrons, engines, smelters, melting furnaces, singeing furnaces, china firing, smoke houses, biscuit baking, steam boilers for feather and hat manufacturers, as well as for heating, gas irons and mangles, washing machines and a multiplicity of other uses which are increasing daily.

For commercial uses it is common both for light and heat to have the gas under increased pressure, or the air supply under pressure, or both and in most appliances primary air is mixed with gas but not in sufficient amount to make a mixture that would be explosive as in the case of the gas engine. When increased pressure is used for lighting the efficiency of the gas mantle light in the use of gas is doubled. Any method that uses the minimum amount of air for complete combustion will give the maximum temperature and hence increased efficiency per unit of gas used. The steam boiler is vastly different in its efficiency depending upon how many pounds of air is used per pound of fuel, and the same principle applies to the use of gas as fuel.

FIG. 48a.

FIG. 48b.

M. Influences Governing the Selection of a Particular Type of Gas for Adoption

First: The first consideration should be the laws existing or that reasonably may be expected to be enacted; if the public demand is for a high candle power, to be obtained by a flat flame burner, carburetted water gas best fills the requirements but in a very small community acetylene gas is the choice if calcium carbide is readily obtainable.

Second: A second consideration is an adequate certain and cheap supply of raw materials. In connection with this your attention is directed to a map issued by the U. S. Geological Survey, entitled "Known productive Oil and Gas Fields of the United States in 1908" and a second, entitled "Coal Fields of the United States" probably also 1908.

In the manufacture of carburetted water gas unless a hard fuel, either anthracite coal or oven coke, as well as oil is available then coal gas would have to form part of the gas plant if for no other reason than to supply retort coke for the water gas generators.

If oil is available in great quantities at a very reasonable price as in California then the oil gas referred to under head D5 and E5 may be chosen.

If gas coal is very cheap then coal gas might be the choice, excluding carburetted water gas or oil gas, provided the candle power provisions do not make it imperative to use these gases.

Third: A third consideration is the variation in the demand which may compel the use of carburetted water gas, even where coal gas is the natural choice, for the ease of supplying sudden large demands, and the small standby cost for materials combined with the smaller capital cost per unit capacity may make this gas cheaper to use in part, even if its cost per unit made seems actually greater than the cost of the same unit of coal gas. The coal gas plants of large cities in all parts of the country, even in the bituminous coal regions, are for this reason supplied with carburetted water gas plants.

Fourth: The capital charge may oftentimes determine choice. Where the difference in cost of production is in favor of coal gas remember that the capital cost of equivalent capacity of water gas is materially less than coal gas and when the productive cost and capital cost are combined the choice may compel the use of carburetted water gas.

Fifth: The land area available is of importance for the space occupied by a coke oven plant is much larger than a retort coal gas plant of equal capacity and a carburetted water gas plant very much smaller than either. Where a small site area is the governing feature then carburetted water gas may be the type of gas best adapted for the conditions.

Sixth: When labor is scarce and remuneration high that process demanding least manual labor may be the type to be chosen. Carburetted water gas frequently best fills this requirement.

FIG. 49.—The First House Lighted by Gas in England.

Seventh: Where the demand for metallurgical coke is great and imperative, the coke oven process will be installed in any event, in which case one of its by-products, gas, may be utilized for the supply of gas in its neighborhood. A carburetted water gas plant is in this case a useful auxiliary, for in dull business seasons when coke is a drug on the market, the coke ovens may necessarily be shut down and the gas demand may be obtained for the time being from the water gas plant. Be sure that the coke demand is reason-

ably certain before building a coke oven plant for furnishing a commercial gas supply, or financial disaster may result.

Eighth: The only available site for the gas works may be in a district where the choice may be the plant producing the minimum amount of dust and dirt. Here acetylene gas or oil gas or carburetted water gas may be the choice to be made.

Ninth: In addition to the choice of the type of gas best adapted to the situation there may be here included a consideration of the system of distribution to be adopted. For suburban districts with

FIG. 50.—The First House Lighted by Gas in Baltimore.

villages quite widely separated, each too small to support a gas plant, a high pressure system may be installed and the manufacturing plant located in the town best situated commercially for economical production costs.

Tenth: Some states have seen fit to pass laws as to maximum price at which gas may be sold. In such cases it would be well to consider fully this rather unusual condition, for it might well be that while the community might be glad to have a supply of gas even at greater charge than the law permits, it might be many

years before a plant would pay a return at the maximum permissible price.

Eleventh: A word of warning with respect to a new plant; do not make the mistake of not looking many, many years into the future. Lay the plant out on paper for the future extensions that are in prospect, for if they are not to be expected, consider carefully whether the plant should be built at all. It does not cost money to look ahead and design a plant showing what is to be done in the future—but it costs money to build a plant to-day and within

FIG. 51.—The First House Lighted by Gas in New York City.

ten years tear it down to build a second and then repeat the process. Depreciation by inadequacy is a cost which is present in the majority of undertakings in a growing country. Minimize this so far as possible. Do not actually build for business so far in the future that interest and depreciation exceeds the saving made by erecting the structures in a single operation. Depreciation by obsolescence cannot be foreseen; be careful to install tried up-to-date apparatus.

STATEMENT OF GAS COMPANIES IN THE UNITED STATES, WITH KIND AND AMOUNT OF GAS DISTRIBUTED

ANNUAL SALES IN CUBIC FEET WITH 000 OMITTED (Brown's Directory, 1910)

State.	No. of companies.	Coal.	Water.	Coal and Water.	Oil.	Natural.	Acetylene.	Gasolene.	Other processes.
Alabama	11	252,410	12,000	217,750					
Arizona	3				52,703				
Arkansas	8	21,771		132,423		$280,394	150		
California	59		8,000		9,133,757	$73,411 78,000 c.f.			
Colorado	11	52,000	8,000	1,163,500		$25,767	74		17,358
Connecticut	24	69,000	1,528,359	1 421,884			$6,020		
Delaware	6	12,985	314,000				$1,810		
District of Columbia	2	2,398,030							
Florida	11		293,165	5,100					
Georgia	12	101,800	147,952	835,601					
Idaho	3	41,000							38
Illinois	68	822,597	1,260,400	2,296,895	5,000			6,320 c.f. $4,500	75,200
Indiana	126	386,790	614,970	1,650,800	11,400	$969,069 900,000 c.f.	80,000 c.f.		
Iowa	82	156,465	1,134,735	759,600	9,000		$700 26,000 c.f.	38,615 c.f. $16,105	5,566
Kansas	56	41,250	27,000			$6,520,140 2,711,076 c.f.	320,000 c.f. $1,112		
Kentucky	17	131,775	25,000	1,187,000	2,500	$218,400			
Louisiana	3	8,600	750,000			$47,000			
Maine	15	98,425	78,240	165,000	1,178 $1,500				
Maryland	16	1,077,800	2,931,567		4,000		338		
Massachusetts	74	970,298	818,032	9,756,857	8,147		1,288		
Michigan	53	774,830	166,784	5,199,990	7,200		250		
Minnesota	22	126,235	586,238	983,761	4,000		62	4,404 c.f. $4,000	
Mississippi	10	90,585	70,440			$13,435	$1,150		
Missouri	30	170,532	44,827	4,465,208	9,500	7,602,612 $681,982	$1,150		6,205
Montana	2	54,000		24,850					

Nebraska	28	16,000	909,950	32,000			$8,200 509 c.f.	6,625 c.f.	29,483
Nevada	3				37,100				
New Hampshire	15	33,225	136,794	225,335	16,000		$500 340 c.f.		
New Jersey	39	1,440,160	4,681,747	2,912,000	1,400				14,125
New Mexico	2	2,000			6,843				
New York	154	1,377,471	24,815,874	19,010,308		$552,428	2,100 c.f.	7,090 c.f.	
North Carolina	11	106,712	60,468	54,416	6,000				
North Dakota	12	52,500		40,000	4,200		$5000 843 c.f.		3,000
Ohio	72	1,986,425	188,114	963,000	8,500	$10,134,668 12,000,000 c.f.	$600 400,000 c.f.		
Oklahoma	28	15,050		21,000	4,000	$1,202,952 887,551 c.f.			
Oregon	6	12,000	826,816		13,300				
Pennsylvania	141	343,359	819,191	11,286,263	3,500	$20,616,068	$800 1,043 c.f.		5,500
Rhode Island	7	76,000	1,545,000				110 c.f.		
South Carolina	4	133,764	45,957						
South Dakota	15	35,000	99,693		2,000		130	3,500 c.f. $6,100	29,750
Tennessee	7	189,184	330,000	419,000					
Texas	21	152,361	543,749	280,000	10,800	800,000 c.f.	65 $500		35,000
Utah	2	7,000		275,000					
Vermont	9	16,000	128,953	27,000					
Virginia	17	309,744	27,000	736,980			1,014		
Washington	9	239,392		843,559			45		
West Virginia	13	350,000	11,500			$438,865			
Wisconsin	38	691,153	171,593	2,849,459	4,700		140	7,009 c.f. $6,300	
Wyoming	1	10,800							
	1,378	15,454,478	46,162,108	70,221,539	9,366,728	24,979,239	834,501	73,563	221,225
					$1,500	$41,774,579	$27,542	$37,005	

GRAND TOTAL (000 included), 167,313,381,000 cubic feet and $41,840,626.00.

NOTE.—Due to intercompany sales in many cities in the United States, the total figures given are in excess of the actual amount of gas manufactured and sold, but the data for the necessary deductions are not available.

N. The Future of the Artificial Gas Business

Judging by the past the gas business is destined to grow in the future as in the past. Gas stockholders received a severe fright when electric light was introduced, but there is little to fear for the growth of the gas business because of electricity until someone invents an economical and successful process to manufacture electricity direct from coal. The fact that gas continues to hold its own even where electricity is manufactured on a large scale with water power makes it unlikely that even such an invention will seriously retard the growth of the gas business. Gas for all purposes where heat units are essential is more economical and is more than holding its own with electricity up to date. It is quite clear that the candle power provisions for gas are bound to be eliminated from legal requirements if for no other reason than that the burner now specified in many statutes will sooner or later go out of common use as the argand burner has disappeared. Should the supply of available oil be removed, as naphtha within twenty years, then high candle power requirements must go. The cornerstone of the gas business of the future, as it was before the discovery of oil, is gas made from bituminous coal and that reason has influenced the selection of a coal gas plant primarily for illustration, but not only for that reason but because its auxiliary machinery and manufacture is the more complex.

While the use of coal gas may increase as pointed out heretofore it is necessary at all times, though more particularly in large cities, to have a water gas plant in combination with coal gas to meet sudden demands for large quantities of gas due to atmospheric variations from day to day, and further the use of gas has displaced in so many ways the use of gas coke that the utilization of this by-product of coal gas by its manufacture into water gas seems imperative.

At this writing the supply of oil shows no prospect of failing for gas making purposes and the use of carburetted water gas is increasing, but in a paper of this kind a reference to such a remote possibility, in view of the constantly increased use of the oil production for other purposes than gas making, seems not out of place.

VIII

PHOTOMETRIC UNITS AND STANDARDS

By Edward B. Rosa

CONTENTS

I. Photometric Units and Nomenclature

The *luminous flux* (F) flowing away from a light source falls upon and illuminates other bodies, the *illumination* (E) being the flux per unit of area. The flux per unit solid angle is the intensity (I). F is measured in lumens, I in candles. The flux per unit of area from a surface is the radiation (E').

The luminous flux is the radiant power multiplied by the stimulus coefficient, which is a function of wave length.

The mean spherical intensity I_s is the total flux F (in lumens) divided by 4π; the intensity I in a particular direction is proportional to the rate of flux in that direction.

By analogy with an electrically charged body, the total *quantity of light* Q on a body is the surface integral of the specific intensity e. Total flux F equals πQ.

Case of extended sources. Disk, plane, cylinder, sphere. Law of inverse squares for case of sphere and circular disk.

Reciprocal relations between radiating bodies. Luminous flux within an enclosure. Equations of definition of photometric magnitudes.

II. Primary and Secondary Photometric Standards

A photometric standard is a standard of light flux, either its total flux or (more commonly) its rate of flux in a particular direction being taken.

The international candle is a unit and not a standard.

The two kinds of primary standards employed in physical measurements; (1) those which are verified or reproduced from standard specifications, and (2) those which are arbitrary and cannot be so reproduced. Examples of such standards.

Flame standards are primary photometric standards of the first kind, although as used are often considered as of the second kind. Incandescent electric lamps are generally employed as secondary standards, but are sometimes used as primary standards of the second kind. Other primary standards.

The most important flame standards are the Harcourt pentane lamp and the Hefner amyl acetate lamp. Advantages and disadvantages of each discussed. Difficulties of both lie (1) partly in the lamp, (2) partly in the fuel, and (3) partly in the atmosphere in which combustion takes place. Each of these three questions discussed for each lamp. The pentane lamp gives more consistent results for a single lamp, but different lamps disagree more than is found for the Hefner. The important difference between a primary standard and a working standard.

Preparation and calibration of electric lamps as photometric standards. Their performance as precision standards, primary or secondary. Method of measurement. Direction of improvement in primary standards.

Introduction

A discussion of photometric units and standards may be divided into two separate parts, the first including photometric units and nomenclature, and the second primary and secondary photometric standards.

The development of the subject of photometric units and nomenclature received a notable impulse through the paper of Professor Blondel, presented to the Geneva Congress of 1896. Since that time various modifications of the proposals then made have been put forward, but no authoritative action on the subject has ever been taken by any national or international body. The nomenclature as approved by the Geneva Congress has, in part, come into general use. There has, however, been a tendency to recognize as few separate photometric quantities as possible, and some of them have been employed rather loosely in more than one sense. This is partly at least due to a lack of clearness in the perception of the physical relations of the various photometric quantities.

I. Units and Nomenclature

1. Case of Point Source

We start with the idea of light as a *luminous flux* radiating or flowing away from the source, and illuminating bodies as it falls upon them. In the simple case of a symmetrical point source the flux is equal in all directions, and since the entire flux falls uniformly upon the interior surface of any concentric sphere, the quantity of the luminous flux per unit of area is inversely proportional to the square of the distance from the source, a law which has been verified by experiment. The quantity of the luminous

flux per unit of area, or the *flux density* at the surface of the illuminated body, is by definition the specific *illumination* E. If we represent the total flux by F we have, therefore,

$$E = \frac{F}{4\pi r^2} \tag{1}$$

where r is the distance from the point source to the body illuminated.

Representing $\frac{F}{4\pi}$ by a single letter I, we have

$$E = \frac{I}{r^2} \tag{2}$$

and

$$F = 4\pi I \tag{3}$$

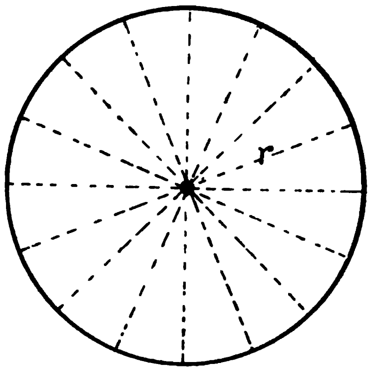


FIG. 1.—Hollow sphere of radius r, and surface $4\pi r^2$, with a symmetrical point source at center, has a total flux F uniformly distributed over it.

I is called the *intensity of the source,* and is equal to the flux per unit of solid angle.

The *illumination* is equal to the intensity of the source divided by the square of the distance (equation 2), and the total flux is 4π times the *intensity* (3).

The intensity I is measured in *candles,** the flux F in *lumens,* and the distance r in *centimeters.* Thus, from a point source of intensity I candles, there is a luminous flux $4\pi I$ *lumens.*

* It is proposed to call the new value of the American candle, which is the same as the English candle and the French bougie decimale, and which is also used by several other countries, the *international candle.*

The *flux density* is the luminous flux per unit of area (normal to the flux in the case of a point source), or the total flux F over an area S divided by the area. If the flux density is variable, S will be a very small area, and F the flux over that small area. Thus a pencil of flux F_1 from a point source falls on a small area, S_1, about the point P, and the surface density or illumination is $\frac{F_1}{S_1}$. (Fig. 2.)

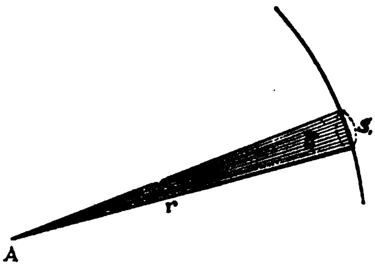


FIG. 2.

2. *Definition of Intensity for Unsymmetrical Sources*

For a symmetrical point source the intensity I has been defined as the total flux F divided by 4π. If the source is not symmetrical, but sends out a total luminous flux F unequally in different directions, then the *mean value of the intensity* (F divided by 4π) is called the *mean spherical intensity* I_s. We thus define the mean spherical intensity with respect to the total flux; and, similarly, the mean hemispherical intensity is the ratio of the flux through a hemisphere to the solid angle 2π, or the average flux per unit solid angle throughout a hemisphere.

The intensity I in any particular direction is the quotient of the flux F_ω through a small solid angle ω in that direction divided by the angle. Thus

$$I = \frac{F}{\omega}, \ \omega \text{ being a solid angle.}$$

Thus, if the pencil of the flux (Fig. 2) occupies an angle ω, the *intensity* I of the source A in the direction of P is $\frac{F}{\omega}$. Thus the *intensity* I is the *angular density* of the flux, as the illumination E is the *surface density*. Thus the expression "the intensity of a source in a particular direction" means the angular density

of the flux in that direction. Therefore, both E and I are flux ratios, lumens per unit area and lumens per unit solid angle, respectively. One lumen per square meter is the lux, and 1 lumen per unit solid angle * ($\frac{1}{4\pi}$ of the total angle about a point) is a *candle.*

If the source is not a point but a small sphere of radius a, the flux $4\pi I$ passes out from a radiant surface $4\pi a^2$. Thus the flux density of radiation, or the *specific radiation,* is

$$\frac{F}{S} = \frac{4\pi I}{4\pi a^2} = \frac{I}{a^2} = E' \qquad (4)$$

Thus we may speak generally of the luminous flux at any point in space, and of the flux density of such radiation. If it falls on a material surface the incident flux density is the *specific illumination* E; as it comes from a luminous or other radiating or diffusing surface, the flux density is the *specific radiation* E′. Although E and E′ are quantities of the same nature, it is convenient thus to distinguish them, and for brevity we may often omit the adjective "specific."

The luminous flux density in space is analogous to electric displacement in electrostatics, which is represented graphically in direction and magnitude by lines of force, which start from positive electricity and terminate upon negative electricity. We think of an electric displacement as occurring in space between two electric charges, but a surface density of electricity occurs only where there is a material conducting body on which the lines of force terminate. In the same way the terms luminous flux and flux density apply generally, both at the surface of the luminous and the illuminated bodies, and in the space between. The *radiation* is the flux density at the source of the flux, and the *illumination* is the flux density or flux per unit area on the surface where the luminous flux is received.

3. Distinction between Luminous Flux and Energy

The total luminous flux F is not to be confused with the total energy flowing from a luminous body. Luminous flux, *or light,* as we ordinarily say, is the physical stimulus which applied to the

* This is an angle subtended by $\frac{1}{4\pi}$ of a spherical surface, and in the case where the solid angle is a circular cone, its section through the apex is a plane angle of 65° 32′ 28″.

retina produces the sensation of light. It is equal to the radiant power multiplied by the stimulus coefficient. This stimulus coefficient is different for every different wave frequency or wave length, and is, of course, zero for all frequencies outside of the visible spectrum. Hence, if W_λ is the power (expressed in watts) for unit of wave length of the spectrum, and K_λ is the stimulus coefficient or *luminous efficiency* whose value varies with the wave length λ, we have for the total power radiated from a body

$$W = \int W_\lambda d\lambda, \qquad (5)$$

the integration being carried through the whole range of wave lengths, including non-luminous radiation.

For the luminous flux,

$$F = \int K_\lambda W_\lambda d\lambda, \qquad (6)$$

the integration being throughout the visible spectrum, K being zero elsewhere.

As the values of K_λ throughout the spectrum are not accurately known, it is not possible to calculate F in general. But by measuring W in watts and F in lumens, we can determine the ratio of the luminous flux to the radiant power in any particular case. One may properly say that luminous flux is due to and is always associated with radiant power, but luminous flux and radiant power cannot, in general, be converted into one another like feet and inches; for, as stated above, the conversion factor, the stimulus coefficient or luminous efficiency, is not a constant like the ratio of feet to inches, but is variable, having a different value for every different wave length in the visible spectrum and falling to zero outside the visible spectrum. "Luminous energy" should, therefore, not be used as synonymous with "luminous flux."

4. *Unit Disk*

Concerning a body charged with electricity, we have the two ideas, (1) the electricity of density σ and total quantity Q on the surface of the charged body, and (2) the flux of force throughout the surrounding space, there being $4\pi Q$ lines of force for a quantity Q of electricity. We do not believe in the fluid theory of electricity in the same way that Franklin did, but we nevertheless find the idea of a surface density of electricity very useful. In the corresponding case with light we may have similarly two distinct ideas, (1) a surface distribution of light over a luminous area of density or *specific quantity* b, and total quantity Q, and (2) a

luminous flux filling the surrounding space and producing an illumination E on any body equal to the flux per unit of area.

We have so far defined illumination and intensity in terms of the flux. Let us now obtain their values in terms of the *quantity of light on the surface of the luminous source.*

The illumination from a very small source is inversely proportional to the square of the distance from the source, and directly proportional to the brightness of the source. Hence, for a luminous plane of unit area, we may write

$$E = \frac{b}{r^2} \tag{7}$$

where b is the total quantity of light on the disk of unit area, which we define as the *brightness,* and the radiation to P_1 at a distance r is normal (Fig. 3). For a point P, at an angle e from the normal, the illumination would be (approximately) proportional to the cosine of the angle e; if the area of the disk is S we should have

$$E = \frac{bS \cos e}{r^2} = \frac{Q \cos e}{r^2} \tag{8}$$

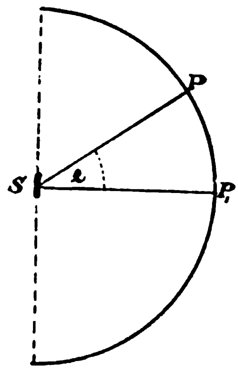


FIG. 3.

Q is the *quantity of light* on the small disk of area S, and is equal to bS (Fig. 3).

The total flux * over the hemisphere illuminated by the disk is πQ.

Thus the total luminous flux F from a small plane disk is π times the quantity of light Q on the disk.

* This is found by integrating the expression for E over the hemisphere. Thus.

$$F = \int_0^{\frac{\pi}{2}} E 2\pi r^2 \sin e \, de = Q \int \frac{2\pi r^2 \sin e \cos e \, de}{r^2}$$

$$F = \pi Q \; [\sin^2 e]_0^{\frac{\pi}{2}} = \pi Q. \tag{9}$$

In electrostatics there are $2\pi Q$ lines of force on each side of a disk charged with Q units of electricity, or $4\pi Q$ total. In the case of luminous flux, the flux is on one side only, and owing to the cosine factor the total is only one-half of what it would be otherwise. Thus, the total is only one-fourth of the flux in the electrical case.

The average illumination over the hemisphere of radius r is $\frac{F}{2\pi r^2} = \frac{1}{2}\frac{Q}{r^2}$ whereas the maximum illumination E_n normal to the disk is $\frac{Q}{r^2}$. Thus the mean is half the maximum. The intensity I has been defined as the *angular rate of flux* in any particular direction. It is, therefore, proportional to the illumination produced in the given direction. Thus, in the case of the luminous disk we have

$$I_n = \text{maximum intensity, normal} = Q,$$

$$I_h = \text{mean hemispherical intensity} = \frac{Q}{2}. \qquad (10)$$

$$I_s = \text{mean spherical intensity} = \frac{Q}{4},$$

$$\text{Thus } F = \pi I_n = 4\pi I_s. \qquad (11)$$

That is, the intensity is numerically equal to the total quantity of light on the small disk *for all points on the normal.* It decreases *to zero* as we pass 90° away from the normal, having a mean value of half the maximum for the whole hemisphere, and is on the average only one-fourth the maximum for the whole sphere. We may, therefore, say that the *hemispherical reduction factor* for the disk is one-half, and the mean *spherical reduction factor* is one-fourth, the disk being supposed luminous on one side only.

Since the total flux F from an area is πQ, where Q is the quantity of light on the area, the flux from a unit of area is πb. This is the radiation E′. Hence, in general,

$$E' = \pi b. \qquad (12)$$

For a small sphere of radius a the total flux is

$$F = E' \times \text{surface.}$$
$$= \pi b \times 4\pi a^2 = \pi Q$$

Also

$$F = 4\pi I.$$

$$\therefore I = \frac{Q}{4}. \qquad (13)$$

That is, for a unit sphere * the intensity is one-fourth the quantity of light on the sphere. If the distribution of light over the sphere is not uniform, the *mean spherical intensity* is still one-fourth the total quantity of light on the sphere, as it is also for a disk. In

* By unit sphere or unit disk, we mean a disk or sphere, the linear dimensions of which are negligible in comparison with the distance from source to receiver.

other words, a sphere produces the same illumination at a given point as a disk of the same diameter and same brightness placed so that the radiation from the disk to the point is normal.

5. Extended Sources

(a) **Circular Disk.** Let AOB represent a circular disk, luminous on one side, of diameter AB, perpendicular to the paper. Each element of the area sends out luminous flux toward the right in all directions (Fig. 4). Let us consider how much of this total flux falls upon a surface of unit area at P at a distance r perpendicular to the center of the disk. The intensity of the radiation

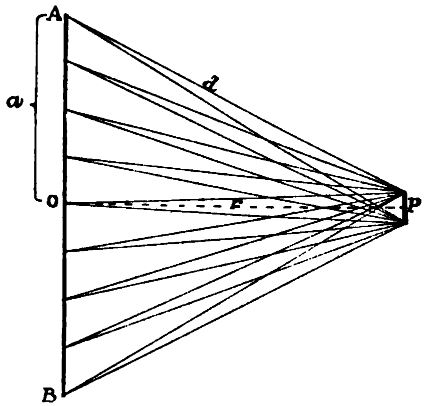


FIG. 4.

in any direction is assumed proportional to the cosine of the angle of emission, the radiation falling on the surface at P is also assumed proportional to the cosine of the angle of incidence. Hence, the flux falling on the area at P is less from the outer portions of the luminous disk AOB than from the center, not only because the distance is greater, but also because the two cosine factors are less than unity. Summing up the radiation from the whole disk, we find that the flux falling on unit area at P, which is the *illumination,* is

$$E=\frac{Q}{r^2+a^2}=\frac{Q}{d^2}$$

where Q is the total quantity of light on the disk, and d is the distance to the edge of the disk.*

* This is shown by integrating over the disk. See paper in Transactions Ill. Eng. Soc., June, 1910, p. 479.

We cannot define the intensity I of the disk in the same way we have for a point or a unit disk, for the radiation is not in a diverging pencil, as from a point. We can, however, define the *equivalent intensity* I_0 as the intensity of a small source at the center O, which would give the same illumination at P. If all the light on the disk were concentrated near O the illumination at P would be greater than that due to the disk. But, if a smaller quantity, $Q_0 = Q \frac{r^2}{d^2}$ were concentrated at O, the illumination at P would be the same. Hence, the *equivalent* intensity I_0 of the disk for the point P is $Q \frac{r^2}{d^2}$. But if the point P be moved nearer the disk, the equivalent intensity of the disk is less than this, for $\frac{r^2}{d^2}$ will be smaller, and if the point P be further away I_0 will be greater. Thus, the equivalent intensity of an extended luminous disk depends on the place at which the flux is being received, instead of being constant for all distances as it is for a point or a sphere. In general, the intensity I, or the angular density of the luminous flux, does not apply to extended sources. The quantity of light Q, however, has a definite meaning in every case. It is the surface integral of b, the brightness, and is not only a very useful quantity to employ in certain calculations, but tends to fix our ideas concerning luminous sources and facilitates exact expression.

In the case of a luminous cylinder of radius a and length l, the quantity of light upon the convex surface is $Q = 2\pi alb$, b being the brightness. The horizontal illumination at a distance r, large in comparison with the length of the cylinder, is

$$E_h = \frac{Q}{\pi r^2}$$

The total luminous flux F from the cylinder is πQ, and, therefore, the mean spherical illumination on the inner surfaces of a concentric sphere of radius *r* is

$$E_s = \frac{\pi Q}{4\pi r^2} = \frac{Q}{4r^2}$$

The spherical reduction factor f for the cylinder is the ratio E_s divided by E_h. Therefore,

$$f = \frac{Q}{4r^2} \div \frac{Q}{\pi r^2} = \frac{\pi}{4} = 0.7854 = 78.5\% \text{ approximately.}$$

Thus an incandescent lamp of one or more straight filaments

should have a spherical reduction factor of 78.5 per cent. This is nearly the value for the tantalum and tungsten lamps, the base of the lamp cutting off some light, and so making it slightly less. A round disk, luminous on both surfaces, has a spherical reduction factor of 50 per cent. This, of course, assumes the cosine law as holding exactly.

The Lighting

The total luminous flux delivered in a given time, that is, the time integral of the flux, may be expressed in lumen-seconds or lumen-hours, according to circumstances. If this is called the *lighting*, and is represented by L, we have

$$L = FT,$$

if F is the total flux in lumens and T is the time in seconds or in hours. The flash of a fire-fly may be expressed in lumen-seconds; the total luminous radiation per gram of an illuminant, or the total lighting during the life of an incandescent lamp, may be expressed in lumen-hours.

The following list of photometric quantities is substantially as recommended by the committee on nomenclature of the Illuminating Engineering Society, and includes the quantities employed in the preceding discussion.

TABLE I

Photometric magnitude	Symbol	Unit	Equation of definition
1. Intensity of light	I	Candle	$I = \frac{F}{\omega}$
2. Luminous flux	F	Lumen	$F = I\omega = \frac{IS}{r^2} = ES = \pi Q$
3. Illumination	E	Lumens or milli-lumens	$E = \frac{F_i}{S} = \frac{I}{r^2}$
4. Radiation	E′		$E' = \frac{F_e}{S} = \pi b = mE$
5. Brightness	b	$\frac{\text{Candles}}{\text{cm}^2}$	$b = \frac{I_1}{s_1 \cos e}$,*
6. Quantity	Q	Candles	$Q = bS$
7. Lighting	L	Lumen-hours	$L = FT$

I, b, Q are expressed in candles. F, E and E′ are expressed in lumens.

$E' = \pi b$ $\quad$ $F = \pi Q$

F_i = incident flux

F_e = emergent flux

m = coefficient of diffuse reflection or transmission

(1 — m) = coefficient of absorption.

$E' = mE$

* S_1 is a small plane area visible from the point for which the intensity I_1 is taken.

What is here called the brightness b has sometimes been called the *specific* or *intrinsic intensity,* and designated by i. But, if i is the specific intensity, the integral of i ought to be the total intensity, and that is not true except for very small plane sources. For spheres, cylinders or extended sources of any shape, it is not true, and the term specific intensity is therefore unsatisfactory.

On the other hand, the brightness b is defined as the quantity of light per unit of area, and the integral of b over the surface of a body, whether it be a self-luminous body of high temperature or a diffusely reflecting body of low temperature, gives the total quantity of light, Q, which multiplied by π gives the total luminous flux from the body.

II. Primary and Secondary Photometric Standards

The fundamental quantity in photometry is the flux of light which produces illumination. We measure the flux from a given source by comparing it with that from a standard source. From a source of light of mean spherical intensity I candles, a total flux of $4\pi I$ lumens occurs. A standard source might be rated in terms of its total luminous flux in lumens, but owing to the fact that it is more convenient to compare accurately the angular rate of flux in a particular direction, or the mean horizontal rate of flux of two given sources, than to compare their total fluxes, it is better to rate photometric standards in terms of their intensity in a particular direction in candles, or the mean horizontal intensity in candles than in terms of their total fluxes. Remembering that the intensity in a particular direction is proportional to the luminous flux in that direction, and is equal to the flux in lumens through a small solid angle ω divided by ω, we see that a standard source of any kind, though rated in candles, is really a standard of light flux, and 16 candles in a particular direction means a flux at the rate of 16 lumens per unit of solid angle in that direction.

The international candle, as the common unit of intensity of England, France and America is generally and properly called, is a unit and not a standard. It will be continued by international co-operative effort, through frequent comparisons of the material standards maintained by the national laboratories of these countries, but the particular standards that are employed by each country in maintaining this unit have not been specified and need not always be the same. The comparisons are made by means of care-

fully prepared carbon-filament lamps, and such lamps are chiefly employed in maintaining the unit constant. But flame standards may also be employed if they are found to be sufficiently reliable, and they can in any case be employed as checks upon the work done through the carbon-filament electric lamps, which are for the present, at least, more reliable. The latter are commonly called secondary standards, although in reality they are at present employed as primary standards.

Two Kinds of Primary Standards

The primary standards employed in physical measurements are of two kinds: (1) those which can be described in such terms that they can be accurately verified or reproduced from their specifications, and (2) those which are more or less arbitrary, and which cannot be accurately reproduced except by copying other standards of the same kind. The international ohm is a standard of the first kind, as it is specified in terms of the resistance of a definite column of mercury at a certain temperature, and it can be reproduced without reference to any other standard of resistance. The meter was originally intended to be such a standard, being defined in terms of the dimensions of the earth. But when it was found that the dimensions of the earth were different from what had been supposed, and that the meter would require a new definition, the reference to the earth was abandoned and the meter became a standard of the second kind, only to be reproduced by reference to other meter bars, copies of itself, of which there were a sufficient number in existence to make it possible to maintain the meter indefinitely in this way. More recently the meter has been expressed in terms of the wave length of light so exactly that it could be reproduced accurately if all length standards were lost. Hence, the meter has again become a primary standard of the first kind. However, meter bars are so permanent that in practice they are verified and reproduced by comparing with one another, without reference to the absolute specification in terms of the wave length of light.

The kilogram was intended to be a natural unit, so defined in terms of the unit of length and the density of water as to be a standard of the first kind. But, owing to the difficulty of deriving it in this way, it is more accurate, as well as more convenient, to regard it as a standard of the second kind, and to verify and re-

produce standards of mass by reference to well-made platinum standards without attempting to derive it according to its original definition.

Thermometers are standards of the first kind, inasmuch as they are referred to the natural interval between the freezing and boiling points of water under standard conditions, and they can therefore be verified or reproduced by referring to the formal specifications.

The unit quantity of electricity, the international coulomb, is defined in terms of the quantity of silver it will deposit under standard conditions when passed through a solution of nitrate of silver. It is, therefore, a primary standard of the first kind.

Primary Photometric Standards of the First Kind

Primary photometric standards may be of the first kind or of the second kind. Although primary standards of the first kind are to be preferred, other things being equal, obviously a reliable and convenient and permanent standard of the second kind is better than an unreliable, inconvenient and temporary standard of the first kind. Many primary photometric standards of the first kind have been proposed, and a considerable number have been used. The sperm candle is made to carefully stated specifications, and has been more widely used than any other photometric standard. But it is a very crude standard. The Carcel lamp in France, the Harcourt pentane lamp in England, and the Hefner lamp in Germany are accepted as primary photometric standards of the first kind in the respective countries. They are made and used according to very elaborate specifications, but as the light is the result of the specified fuel burning in a specified lamp, surrounded by a specified atmosphere, the standard is not merely the lamp, but the combination of lamp, fuel and atmosphere, the two latter of which are constantly changing. For use in ordinary gas photometry flame standards are convenient. But for precision photometry, in general, or for determining and maintaining a photometric unit, it is not unfair to say that the best of flame standards is not as convenient or reliable as primary standards ought to be.

The difficulties in the use of flame standards are, therefore, partly in the lamp, which is the more or less permanent part of the combination; partly in the fuel, which is often found not to conform to the specifications, and in some cases is liable to change on

standing even if it conforms originally to specifications, and partly to the atmosphere, which is constantly changing with respect to barometric pressure and aqueous vapor, while in and about the lamp it changes also with respect to carbon dioxide and oxygen content. All these variations affect the light as a flame standard, and make the errors of measurement many times greater than those made on carbon-filament lamps. By making a long series of measurements, the accidental errors are largely eliminated, and a mean result may be obtained which is surprisingly good in view of all the difficulties. But there are constant sources of error that are not so eliminated, and perhaps the most perplexing are due to the lamp itself. For example, although Hefner lamps are made by different makers very carefully from the same specifications, there is a range of 2 per cent between the highest and lowest values of eight Hefner lamps belonging to the Bureau of Standards, four from one German maker and four from another. There are two different devices in use for observing the height of the flame, but all (or nearly all) the lamps conform to the specifications. If one requires only that his Hefner lamp be correct within 2 per cent, all these lamps are satisfactory. But as primary standards they ought not to differ so much independently of fuel and atmosphere. In the same way, standard Harcourt pentane lamps differ several per cent in candle-power, using the same fuel and operating them under the most favorable conditions. At the Bureau of Standards we have tested pentane lamps from two English makers and one American maker. The two Chance lamps tested have the highest candle-power, averaging about 9.9 international candles under standard atmospheric conditions, namely, 8 liters of water vapor per cubic meter of air, and standard barometric pressure. The Sugg lamps tested average less than 9.7 candles, about 2.5 per cent less than Chance lamps. American-made pentane lamps also average about 9.7 candles.

The standard Harcourt pentane lamp was supposed originally to give 10 British parliamentary candles, and there was supposed to be no appreciable variation among different lamps. The National Physical Laboratory adopted a particular lamp of this kind as its primary standard. When the international candle was fixed by agreement between the national laboratories of England, France and America the Bureau of Standards made a change of 1.6 per cent in its photometric unit, in order to come into agreement with

England and France, and at the same time to bring the gas and electric industries of America to a common standard by bringing the new unit midway between the old unit of the Bureau, which was used by the electrical industries, and the average value of the unit used in the gas industries. Theoretically, therefore, the standard pentane lamp should give 10 international candles. But it happens that the particular standard pentane lamp of the National Physical Laboratory apparently has a slightly higher value than the average, and the English maker of the lamp has been unable to furnish us a lamp giving the same candle-power. The Bureau placed an order for a lamp to agree with the standard of the National Physical Laboratory, as shown by direct comparisons made at the National Physical Laboratory. After several attempts on the part of the maker a lamp was accepted having about 1 per cent lower value. The Bureau has never tested a pentane lamp of any make having a value as high as the National Physical Laboratory standard. The values found range from 1 to 5 per cent less. Hence, it is evident that the pentane lamp as a primary standard cannot be a complete success until different makers following the same specifications can produce lamps agreeing better in value, and until the lamps produced by any experienced maker agree better among themselves than they now do. At the Bureau of Standards we have made some progress in locating the source of the differences, and hope soon to see a great improvement in this respect.

The second source of trouble with pentane lamps is the fuel. Pentane (C_5H_{12}) is a very volatile hydrocarbon, distilled from gasoline. It is classed as explosive, and should be shipped in strong sealed cans and stored and handled with special precautions. It costs the Bureau of Standards $3.50 per gallon, and is consumed in considerable quantities. It is distilled between 25° and 40° C., and in summer in an open can evaporates rapidly at laboratory temperatures. The flame is ordinarily fed by the mixture of air and pentane which come over from the saturator. But in hot weather instead of air entering the inlet, pentane vaporizes so rapidly that it flows out through both outlet and inlet, the vapor escaping through the air inlet, passing out into the atmosphere of the laboratory, and so causing the pentane to disappear at, perhaps, double the normal rate. Hence, pentane lamps, as ordinarily constructed, cannot be used satisfactorily in summer in

southern latitudes. Slight modifications in the lamp can be made to overcome this difficulty.

Moreover, as pentane is not a simple compound, but contains homologous compounds which are not completely separated even by repeated distillations, the density changes as evaporation proceeds, and hence the reservoir must be emptied and refilled with fresh pentane from time to time, in order to keep the fuel within the specifications and the light of the flame sufficiently near to its normal value.

The light of a pentane flame, like other gas flames, is very sensitive to impurities in the atmosphere and to drafts or air currents. There must be excellent ventilation of the room and plenty of pure air supplied to the flame, but not too much. The removal of the products of combustion and the screening of the lamp from air currents, as well as the regulation of the supply of pentane and the detailed manipulation of the lamp, all call for experience, patience and skill in high degree, in order to get consistent and reliable results from a pentane standard.

Of course, the atmospheric humidity must be carefully determined every time a set of measurements is made, and the barometer must be read in order that humidity and pressure corrections may be made. These corrections are considerable, the humidity correction, which is the larger of the two, sometimes amounting to 10 per cent.

These remarks apply only to pentane lamps which are used for the purpose of relatively accurate measurements. As working-flame standards they may be used with fewer precautions, if approximate results are sufficient.

When a flame standard is employed for testing illuminating gas, the humidity and barometric corrections are not applied, as the gas flame is affected practically by the same amount, and the test is intended to demonstrate the quality of the gas and not the amount of light given by the given test burner at that particular time. In other words, 20-candle-power gas is not gas that always gives 20 candle-power in a particular burner when consumed at a stated rate, but gas of standard light-giving properties, that is to say, it gives 20 candle-power when burned at a given rate in a particular burner in a standard atmosphere, which is a pure atmosphere containing 8 liters of water vapor per cubic meter and at normal barometric pressure. In winter, when the humidity averages less

than normal, the light will be greater than the average. In summer, when the humidity averages greater than normal, the light will be less than the average, and may be 10 per cent less. Thus, flame standards are for this reason well adapted to serve as working standards for testing the light-giving properties of gas and oil. But for primary standards, intended to maintain a photometric unit, they are not as well adapted as they would be if unaffected by the atmosphere.

Hefner lamps have some important advantages over pentanes, and some marked disadvantages. Whereas the standard Harcourt pentane lamp is bulky, complicated in construction, relatively laborious to manipulate, and expensive both in first cost and in fuel, the Hefner amylacetate lamp is small and very portable, simple in construction, easy to assemble and make ready for use, and less expensive in first cost and in fuel. The latter costs the Bureau $3.00 per pound, but so much less is employed that it costs less per hour than pentane at $3.50 per gallon.

Its disadvantages in comparison with the pentane standard are (1) its small candle-power, (2) the redder color of its flame, (3) its more unsteady flame, and (4) the greater difficulty of maintaining the correct flame height.

The Hefner flame has a horizontal intensity of 0.9 candles when the flame is 40 mm. high, as officially prescribed in Germany. We find at the Bureau that the flame burns about as steadily and is nearly as easy to manipulate when maintained at 45 mm., at which height it gives 1 international candle, or 0.1 candle more than at 40 mm. This change in a standard lamp is made by placing a ring 5 mm. thick under the support of the sight which is used to regulate the flame height. To obtain a suitable illumination on the test screen of the photometer, a standard of 1 candle-power must be placed quite near, and errors due to slight variations in distance are much greater than for a 10-candle-power standard. In practice, both a shorter distance and a weaker illumination are employed with the Hefner standard.

The color difference between standards, or between a standard and a light source, is necessarily a source of uncertainty, and with modern electric and gas lamps the demand is for whiter standards. The Hefner is the reddest standard in use, and its color is one of its most serious objections. However, color screens are necessary to pass from one color to another, and the difference between the

pentane color and the Hefner color is not enough to make this a deciding consideration, as between the two lamps. The voltage on a carbon-filament lamp necessary to give a color match with several different flame standards is as follows:

To give 4 watts per candle	=110 volts.
To match the kerosene lamp	=102-108 volts.
To match the Carcel lamp	=98 volts.
To match the pentane lamp	=91 volts.
To match the Hefner lamp	=86 volts.

The flame of a Hefner lamp is very easily disturbed by air currents, and the tip is in almost constant motion vertically and laterally, so that the flame must be screened very carefully, and then must be watched constantly by an assistant, and readings made only when it is at the right height and in correct position. The tip is only slightly luminous, and yet the height must be maintained constant to a fraction of a millimeter. Different observers may differ sensibly in their judgment as to when it is right, although this source of error is smaller than would be supposed.

The amylacetate is so volatile that the top of the wick is below the top of the wick tube. As the room temperature rises, the wick must be lowered to keep the height of flame constant, and this makes the flame more unsteady. At summer temperature, such as 25° to 30° C., the flame is much more unsteady than at 15° to 20° C. In this respect (less satisfactory operation in hot weather) both the pentane and amylacetate lamps and candles are inferior to kerosene-oil lamps.

Because the Carcel lamp is so little used in this country, or anywhere outside of France, and because our limited experience at the Bureau has shown it to be unsatisfactory, nothing will be said of it as a standard.

Candles have been of enormous service in practical gas photometry, but they cannot be seriously considered at the present day as standards. Kerosene-oil lamps are much more convenient and reliable, and we hope in the near future to publish experiments made at the Bureau showing that as secondary standards for practical photometry they may be used with excellent results.

To sum up in a few words, it may be said that as primary photometric standards of the first kind, there are the pentane and Hefner lamps about equally entitled to consideration, each possessed of important merits, but also of serious limitations and defects. A

given pentane lamp is probably more consistent with itself than an average Hefner, but different pentane lamps differ more than Hefner's do. No other standard of the first kind equals them in constancy and reproducibility, and no other is used where accurate results are attempted.

The radiation from incandescent platinum at its melting point was long ago proposed by Violle as a primary photometric unit of the first kind. But, although enormous progress has been made in obtaining and maintaining and measuring high temperatures, and several serious attempts have been made to make Violle's proposal practicable, nobody has ever succeeded in doing as well with it as can be done with flame standards. Drs. Waidner and Burgess, of the Bureau of Standards, have made an interesting proposal, namely, to employ the radiation from a black body at a particular temperature, for example, at the melting point of platinum, but they have not as yet attempted to realize it in practice. Dr. Steinmetz has recently also made a new proposal for a primary photometric standard of the first kind, but the realization of this proposal to the extent of obtaining a standard of precision seems very difficult, and so far as I know has not been attempted.

Photometric Standards of the Second Kind

The most successful photometric standards of the second kind are carbon-filament incandescent lamps, which have been employed for many years as convenient working standards, and in recent years have been employed in making careful comparisons of the photometric standards of different countries. Their use is so important and their operation under the best conditions is so admirable that I wish to present briefly the method of their preparation and use and records of their performance. Such lamps cannot, of course, be made accurately to specifications, but if they are sufficiently permanent they may be employed to maintain the unit of light for an indefinite period. Probably nothing is more permanent than pure carbon, sealed in a vacuum and kept at ordinary (room) temperatures. Hence, if carbon-filament lamps can be prepared which will not change appreciably when burned, say 100 hours, under working conditions, there is reason to believe that they will remain constant for a long period of years (barring accidents) and that a group of such lamps will afford a means of maintaining the unit of light constant for a long time. How long

and how accurately can, of course, only be determined by experience.

Carbon-filament incandescent lamps are usually operated as standards at a constant voltage, the current being measured as a check. Sometimes they have been measured at constant current, the voltage being varied slightly, if necessary. If the lamps have constant resistance, of course these two methods would amount to the same thing. But, as carbon-filament lamps do not have constant resistance, but generally show a decreasing resistance, followed after a longer or shorter period by an increasing resistance, it becomes a matter of prime importance whether the best performance can be secured by operating lamps regularly during their useful life as standards at constant voltage, or at constant current, or whether still better results can be obtained by operating them at constant watts. Obviously, if the radiation from the surface of the filament is unchanged, and the bulb does not blacken or change its absorption, the most constant candle-power will be secured by operating the lamps at constant watts; a constant rate of energy supply and a constant conversion factor giving a constant flux of light. But, whether the radiation from the filament and the absorption in the bulb will be constant at constant watts could only be determined by experiment.

At the Bureau of Standards we have investigated this question very carefully, and to obtain the highest possible precision have made use of a double-precision photometer, with special recording cylinders, having two observers measure the same lamp simultaneously, and a third observer measuring the current and voltage of the lamp at once by means of two standard potentiometers. A single determination consists of the mean of a large number of readings, each recorded without the observer taking his eye away from the photometer, and as the observer does not know any of his readings until they are all completed, he reads without prejudice. By this means each observer is a check upon the other, twice as many determinations can be made in a given time as by a single photometer, and by the use of Dr. Middlekauff's direct-reading scale all calculations of candle-power are eliminated, the value of each determination in terms of the mean of the group of standards employed being read off directly from the record sheet.

In this way it has been found that with lamps in which no blackening occurs the best results are obtained by keeping the watts

constant instead of using them at constant voltage. Life curves have been made of a large number of standards, and each curve divided into the period of seasoning and the period of useful life as precision standards. If they are burned at constant volts, the seasoning is carried on until they reach constant resistance. This is a longer or shorter operation, depending on the temperature (or watts per candle) at which they are seasoned, but is not the same for different lamps. If, however, they are to be burned at constant watts, it is not necessary that the seasoning be continued to minimum resistance; when the filaments have nearly reached that condition they may be used with perfect satisfaction, and long after the resistance has reached its minimum and has increased appreciably the lamp is still a reliable standard, provided only that the watts have been kept constant, and, of course, provided that blackening has not occurred.

Blackening can be detected by the decrease in the light of the lamp before it can be seen on the glass. To reduce it to a minimum the lamps should be made and selected with great care, and the filaments should preferably be mounted in larger bulbs than is ordinarily done. Dr. Fleming, of London, many years ago advocated the use of large bulbs for incandescent-lamp standards, but as the quality of lamps improved it did not seem necessary to use them, and hence nearly all laboratories used the ordinary-sized 16 candle-power lamps for standards of the best quality. We have found in our recent work at the Bureau of Standards, however, that lamps in larger bulbs give better results.

We have seasoned and carefully measured nearly 200 standards as above described, and selected the best for primary standards. A few of these have been burned for 200 hours after seasoning without the candle-power changing more than a few hundredths of a candle. Such lamps would serve as reference standards in a photometric laboratory for many years, perhaps for a century, without being burned as many hours as they have been burned in these special tests. There should be no depreciation while they are not burning, for what is more permanent than pure carbon, preserved in a vacuum at ordinary temperatures?

As to the precision of measurement of carbon-filament electric lamps, on such a precision photometer as described above, the mean error of the determination of candle-power on any lamp at one time is about 0.2 per cent, whereas the mean error of the average

value of six lamps measured at one time is about 0.1 per cent. If a group of six lamps be measured by four different experienced observers (as is done at the Bureau in work of the highest precision) the mean of the four will be still less in error. These figures are the results of a large number of experiments with rotating standards, of the same color, and stationary standards may be measured with substantially the same accuracy.

With such precision of measurement and a life performance of standards such as described above, it would seem as though the unit of candle-power not only of a commercial laboratory, but also of a national standardizing laboratory, or even of a group of national standardizing laboratories, could be maintained for a long period of years by carbon-filament incandescent lamps more constant than has been possible heretofore with flame standards or any other form of primary standard as yet realized.

However, there are possibilities of improvement in flame standards, and, of course, possibilities of some new primary standard appearing which shall surpass any flame standard as yet proposed. What I wish to emphasize is, not by any means that incandescent lamps are the final standards or that they are satisfactory as primary standards, but that they *really are,* as now used, *primary standards,* and that by their use a photometric unit can be maintained so well that until the difficulties of heterochrome photometry are overcome, and until the demands for precision in practical photometry are considerably increased, we need not fear that the international candle will drift far enough from its present value to be serious. The progress that has been made in photometrical measurements in the 14 years since the Geneva Congress is gratifying. Then it was believed that the Hefner unit and the bougie decimale were practically equivalent. The uncertainty in the relative values of the standards of different countries amounted to several per cent. Now the corresponding uncertainty is not or need not be more than a few tenths of 1 per cent, so long as standards of a single color are employed. It remains to accomplish as much for standards of a whiter color, and to fix the ratios in passing from one color to another.

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IX

THE MEASUREMENT OF LIGHT

BY CLAYTON H. SHARP

CONTENTS

Photometry.
  Definition and scope.
  Quantities to be measured.
Measurements.
  Are relative to a standard.
  Made by zero method, using the eye as instrument for determining equality.
  Difficulty due to color difference.
Apparatus, general.
  1. Sight-box, photometer head, or, for short, photometer, for producing contiguous illuminated fields.
  2. Apparatus whereby intensity of one or both fields may be varied according to known law.
  3. Standard source of light.
Varying the intensity.
  Distance.
    Effect of area of sources.
    Apparent candle-power.
  Sector disc. Talbot's Law, Napoli, Brodhun, Hyde.
  Diaphragm. Cornu's cat's-eye. Lens. Diffusing plate.
  Polarization.
  Inclined plate.
  Varying source—height of flame, voltage.
Sight-box.
  Fields must be contiguous or adjacent.
  Equality principle. Contrast principle.
  Lambert or Rumford.
  Bouguer-Foucault.
  Wedge.
  Elster-Joly block.
  Bunsen.
    Grease-spot. Disappearance. Contrast—Rüdorff mirrors. Leeson built-up disc. Theory. Construction. Errors in use. Limitations. Accuracy.
  Lummer-Brodhun.
    Plain. Contrast. Sensibility.

Practical apparatus.
- **Precision bar photometer. Scales, equal part, proportional, direct reading.**
- **Industrial: gas, electric.**
- **Portable and illumination photometers.**
  - **Weber, Martens, Blondel, Sharp-Millar.**

Auxiliary apparatus.
- **Lamp rotators.**
- **Distribution, elevating lamp, three mirror.**
- **Arc-lamp apparatus. Long arm.**

Integrating and summation apparatus.
- **Blondel, Matthews, sphere.**

Heterochrome photometry.
- **Equality of contrasts—Leeson disc.**
- **Visual acuity.**
- **Flicker photometer.**
  - **Rood, Simmance-Abady, Whitman, Schmidt & Haensch.**
- **Spectro-photometers.**
  - **Vierordt, Lummer-Brodhun, Nichols, Brace.**
- **Three-color apparatus. Ives colorimeter.**

LECTURE I

Definition and Scope

Photometry is broadly defined as the science of the measurement of light. Ordinarily the name has been used to refer to the measurement of the intensity of sources of light, since this has been the measurement most commonly made. The measurement of illumination as distinct from intensity of a source has come into much greater prominence in recent years, and the term "illuminometry" has been used for this class of measurements. Essentially, there is no difference between illuminometry and photometry, all photometric measurements being essentially measurements of illumination or brightness; hence, we may say that the term illuminometry includes the term photometry. The term photometry, however, is very much preferable, and is properly used to include all the branches of the measurement of light and illumination.

Quantities Measured

The fundamental quantity with which photometry has to deal is luminous flux. The intensity of a source is its flux per unit solid angle. The illumination is flux per unit area. These three quantities, flux, intensity of a source and illumination, are the chief ones with which photometry has to do; while specific intensity—

specific flux, etc.—are also quantities included in the ordinary scope of photometry.

Measurements

The Eye as a Photometric Instrument. The normal human eye being the only instrument which is sensitive to light, in as far as light concerns the normal human being, it is the eye which must constitute the fundamental photometric instrument. The eye by itself is incapable of determining with any accuracy the intensity of a source of light or the intensity of illumination. Moreover, the eye is incapable of forming any correct estimate of how many times one light is brighter than another. It is only by the use of special methods that the eye is adapted to photometric work. These methods depend upon the following properties of the eye:

First. The eye is capable of determining with a considerable degree of nicety the equality of the brightness of two contiguous illuminated fields. With special devices the difference in brightness which can be detected by the eye is quite small, therefore photometric measurements may be made by a zero method relative to a standard of luminous intensity or of illumination.

Second. Any given eye under given conditions is capable of detecting a certain degree of contrast with a certain illumination, or of just distinguishing certain objects with a certain illumination; for instance, a certain minimum illumination is required with a given eye in a given condition to enable a certain print to be read. This point is not very well defined, but is sufficiently well defined to enable photometric measurements of a certain class to be made in accordance with the principle involved. This is called the "visual-acuity" method. There is also a zero method dependent on the disappearance of flicker. This will be discussed in its proper place.

By the zero method where the eye is comparing the brightness of one field with that of another, and deciding when they are equal, difficulty is encountered whenever the illumination of the two fields differs in color. Color differences represent differences in quality, and, from a theoretical point of view, substances which differ in quality cannot directly be compared quantitatively. The practical effect of color difference in photometry by the zero method is to make the error of measurement considerably greater, and to give rise to personal differences between different individuals who ap-

praise the different colors according to different personal standards. Thus color differences constitute one of the greatest inherent difficulties in ordinary photometry. In using the second or the liminal method referred to above, color differences are eliminated, since only one color is observed at a time. The illumination observed by this method is given a value proportionate to its usefulness in enabling objects to be distinguished. This value may differ considerably from that obtained by the zero method.

In the flicker method color differences are eliminated.

Methods—Direct Comparison and Substitution

There are two general methods employed in the use of photometric apparatus. In the *direct-comparison method* the apparatus is set up in such a way that the source of light to be measured is compared directly with the standard source, one being placed on one side of the photometric apparatus and the other on the other, and the balance secured. In making measurements after this method, many precautions are required to eliminate the errors due to one-sidedness of the apparatus, or to a tendency of the observer to favor one side rather than the other. In working by the *substitution method,* the comparison between the source of light to be measured and the standard is indirect. The procedure is, first, to set up the standard source of light and compare with it a constant source of light of convenient intensity. Then the standard source of light is removed and the unknown source is substituted for it. The unknown source is then compared with the constant intermediate source of light, and its value in terms of the standard is computed from the two sets of measurements. This method of procedure has the advantage over the direct-comparison method that all errors due to lack of symmetry in apparatus, etc., are eliminated. The substitution method is to be preferred to the direct-comparison method in the great majority of all cases arising in photometry.

Apparatus for Zero Method

Any apparatus for making photometric measurements according to the zero method, that is, by balancing the brightness of two adjacent or contiguous fields, consists essentially of the following elements: First, an arrangement by which the two adjacent or adjoining fields are obtained, one of the fields being illuminated by the standard light and the other by the light to be measured.

Second, in an arrangement by which the intensity of the illumination of one or both the fields may be changed according to some known law until equality is secured. Third, a standard source of light.

The apparatus by which the contiguous fields are obtained is called the sight-box or photometer head, or, for short, the photometer. Properly speaking, the photometer includes the whole apparatus, but the distinction here noted is in many cases a convenient one to make, and no confusion should arise because of the use of a term proper to the whole apparatus for a part of the same.

The question of a standard source of light is a separate one which has been treated by another lecturer.

Apparatus for Varying the Illumination

Variable Distance. The simplest and most common way to vary the illumination on the photometer disc in a known manner is to vary the distance between the photometer disc and the source to be measured. For point sources the illumination produced is inversely proportional to the square of the distance between the source and the illuminated surface, the illuminated surface being placed at right angles to the rays. Hence, by varying the distance of either of the sources of light, or by moving the photometer into some position along the straight line adjoining the sources, the desired equality of illumination may be obtained. The mathematical relations are as follows:

If E is illumination on the two fields of the photometer, I is the candle-power of the unknown source, I′ the candle-power of the comparison lamp, r the distance between unknown lamp and the photometer disc, and r′ the corresponding distance for the comparison lamp,

$$E = \frac{I}{r^2} = \frac{I'}{r'^2}$$

or

$$I = I' \frac{r^2}{r'^2}$$

The most common arrangement is to set the lamps to be measured at the extremities of a straight horizontal track or bar. On this bar is a carriage to which the photometer head is attached. The carriage is moved along between the lights until the desired equality is obtained. The results are computed according to the formula

$$I = I' \frac{r^2}{r'^2}$$

in which I and I′ are the intensities of the two sources of light, and r and r′ the distances between the respective sources and the photometer disc.

It is not infrequently desirable to alter the distance between only one lamp and the photometer disc. For instance, the photometer may be stationary, and the distance of the comparison lamp may be adjusted to give equal illuminations. In this case the product $I'r^2$ does not change, and the formula for the photometer is

$$I = \frac{\text{constant}}{r'^2}$$

Or the comparison lamp and the photometer carriage may be fastened rigidly to each other so that the distance r′ is constant and the distance r varied. In this case the illumination on the photometer disc is constant at all times, a feature which has some advantages. The formula in this case becomes

$$I = \text{constant} \times r^2.$$

A further modification of the variable distance method is an arrangement wherein the length of the path of light is varied by moving a mirror or pair of mirrors set at right angles to each other. The photometric law remains the same.

Limitations of Variable-Distance Method. In employing the inverse square law it is necessary to remember that it applies in all strictness only to point sources of light, and that for sources of linear dimensions large in comparison with the distance at which they are measured, the law does not apply. This is due to the fact that an element of the luminous body which is not situated in the line normal to the photometer disc sends rays to the disc which impinge upon it at an angle other than 90°, and consequently produce a smaller illumination than if they fell normally. Moreover, the angle of emission of these rays from the luminous surface, supposing the luminous surface to be parallel with the photometer disc, is not 90°. These two effects, according with Lambert's cosine law, produce a diminution in the illumination. It is therefore necessary that the angle at the photometer disc subtended by the source of light should be below a certain limit. The rule has been given that the linear dimensions of the source of light should not be over five times the distance between the source of light and the photometer disc. It is safe, and usually entirely convenient, to keep far within the limitations of this rule.

It is necessary also to see that the angle of incidence of the light upon the two fields of the photometer is the same. If the angle is different on one side from what it is on the other, an error will be introduced according to Lambert's cosine law. Any such error as this, however, may be eliminated in the substitution method.

Apparent Candle-Power. It is frequently convenient to express the photometric properties of a combination, such as a lamp with a reflector, or a very extended source of light, in terms of the candle-power of a point source which would produce at a given distance the same illumination as the arrangement to be measured produces. For example, the law of inverse squares cannot be assumed to hold for a lamp with a concentrating reflector within relatively short distances from the lamp. However, for purposes of illumination computation, it is important to know what the equivalent candle-power of the combination is at some practical distance. To this quantity the term "apparent candle-power" is applied, the distance at which this apparent candle-power is measured being also specified. In reflector measurements the apparent candle-power at a distance of 10 feet is commonly given. This means merely that when the lamp and reflector are measured with the photometer 10 feet away the illumination which is produced is equivalent to that of a lamp alone having the candle-power given.

Rotating Sector Disc. If an opaque disc from which equally spaced sectors of definite angular dimensions are cut is placed in the path of a beam of light and rotated rapidly, the amount of radiation passing through the open sectors bears to the total radiation the same ratio that the angular aperture of the open sectors does to 360°; that is, if the open sectors aggregate 36° in aperture, 10 per cent of the radiation will pass through. If the light so diminished falls upon a screen, and the rotation is sufficiently rapid, the eye will observe the screen uniformly illuminated, and the impression made upon the eye will be, in accordance with Talbot's law, the same as if the same flux of light fell upon the screen in a steady stream as actually falls on the screen in the intermittent stream transmitted by the disc. Therefore, physiologically, as well as physically, the beam transmitted by the rotating disc varies as the ratio of the angular aperture of the open sectors to the total periphery of the disc.

Verification of the Law of the Disc.* By a series of careful experiments, Lummer and Kurlbaum have shown that for lights of the same color Talbot's law held for the disc within the errors of observation.

As a result of experiments by Ferry † doubt had been cast on the validity of Talbot's law when lights of different color are compared by means of the sector disc. This question has been investigated by Hyde,‡ whose careful experiments have shown that Talbot's law applies to the rotating-disc method within the errors of observation, both when lights of the same and different colors are compared with all apertures of the disc from 15° to 240°.

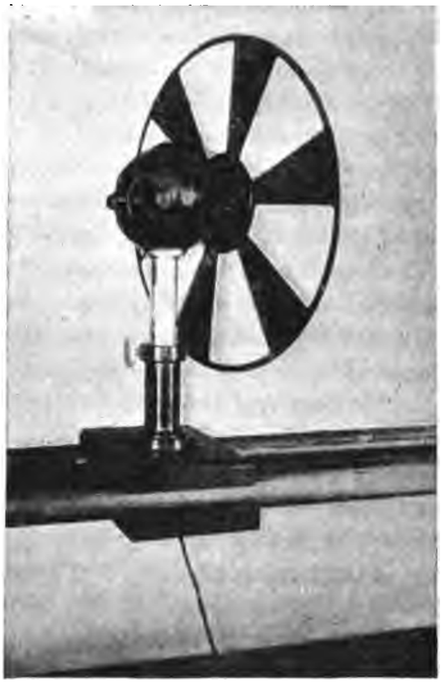

FIG. 1.—Sector Disc with Fixed Apertures.

* Zeitschrift für Instrumentenkunde. Elektrotechnische Zeitschrift, Aug., 1896.

† Phys. Rev., Vol. 1.

‡ Bull. Bureau of Standards, Vol. II, p. 1.

Practical Forms of Sector Disc. The sector disc, which is a most important adjunct in photometric work, can be made either with fixed openings or with variable openings. With fixed openings, it is convenient as a means for reducing the intensity of a beam of light in a known ratio, an operation which is often desired in order to bring a given measurement within the range of a given photometer bar. A fixed disc of this sort, as used by the Bureau of Standards, is illustrated by Fig. 1. Evidently one motor may

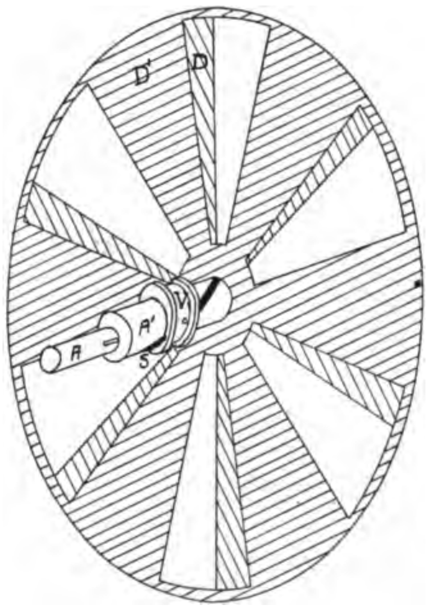

FIG. 2.—Sector Disc.

be supplied with a series of discs, so that a variety of ratios are obtainable, but in any case the fine variations of photometric settings must be made by some other means. A disc may be constructed to produce any required diminution from 50 per cent downward by taking two equal metal discs, out of which equally spaced sectors are cut, of such dimensions that the open sectors occupy one-half of the disc. These are mounted face to face on a shaft, and are provided with a clamp to hold them together in any position. By sliding the discs over each other, the amounts of the open sectors of the combined disc may be varied at will, and the ratio may be read from a graduated scale on one of the discs.

In the construction shown in Fig. 2, the area of the open sectors may be varied while the discs are in full rotation, thereby constituting a device by which complete photometric settings can be made. The sector disc D is mounted on the axis A, while a similar disc D′ is fastened to the hollow sleeve A′, fitting over the axis of the first disc and rotating with it. A′ is pierced with the spiral slot S, while A has a longitudinal groove of the same width. A hollow sleeve V fits over the sleeve A′ and carries a pin which passes through the spiral slot and terminates in the longitudinal groove. A longitudinal movement of V, which can be effected by means of a lever or a micrometer screw when the discs are rotating, displaces the one disc with respect to the other, and varies the

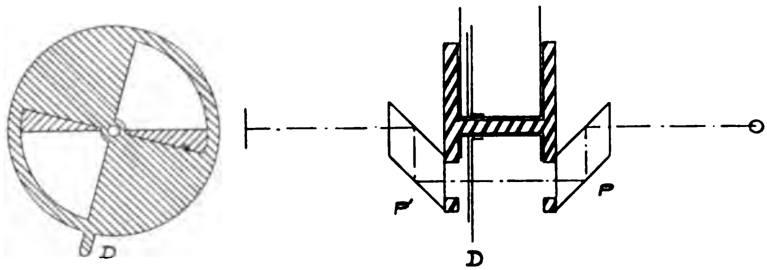

Fig. 3.—Brodhun's Sector.

effective aperture of the combination. The lever or micrometer screw is calibrated to show the ratio of the disc and can be read without stopping the disc.

Brodhun's Variable Sector. Brodhun has not only constructed a variable rotating-sector disc, in which by special optical arrangement the actual angle between the sectors can be read from the disc while rotating, but he has also produced another and much simpler apparatus for changing the intensity according to Talbot's law. In the latter apparatus the variable sector remains fixed, while the beam of light is caused to rotate about it. The arrangement is shown in Fig. 3. The beam of light striking the Fresnel prism P is twice reflected to the Fresnel prism P′ on the opposite side of the sector D, by which it is returned to its original axial direction. The prisms are rotated rapidly, and the photometric setting made by the aid of the adjustable sector disc D, the position of which, since it is stationary, can be read at once from an affixed scale. In the form in which it is constructed by Schmidt &

Haensch, this apparatus is adapted to the measurement of light in rather small beams. There is no reason, however, why the principle should not be applied to a larger apparatus made with mirrors instead of prisms.

Hyde's Variable-Sector Disc. For the special purpose of spectrophotometry, in which the beam to be photometered enters the narrow slit of a collimator, Hyde has produced a very simple form of

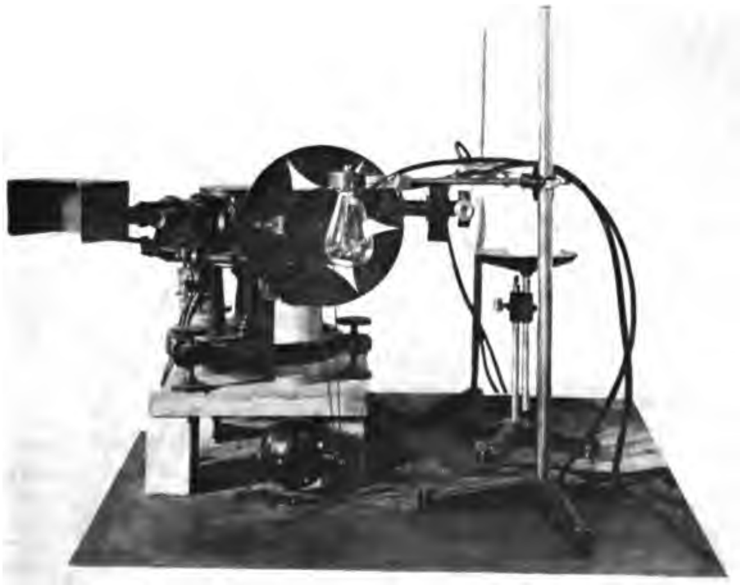

FIG. 4.—Hyde's Sector.

variable-sector disc. In this form (Fig. 4) the apertures of the disc are not straight and radial, but are curved in such a way that near the center of the disc the apertures are nearly 100 per cent, and the aperture varies from that to zero at a point near the circumference of the disc. It is evident that if a slit which is to receive light is placed so that it lies at right angles to the axis of the disc, the amount of light which it will receive will vary with the position of the disc with respect to it. That is, when the beam of light reaching the slit passes through the openings near the

center, the diminution introduced by the rotating disc will be small. This diminution can be increased steadily by a lateral motion of the disc. If the relation of the disc carrier, with respect to the slit, is fixed in the apparatus, the position of the disc, as indicated on a scale with vernier, will give, by a previous calibration, the percentage of light which the disc is transmitting.

Use of Diaphragms. A diaphragm may be used in several ways as a means for diminishing the intensity of a beam of light. If, for example, the source of light is a uniformly illuminated diffusing surface, the amount of light which it emits varies directly with its area, so that if a diaphragm is placed before it the light emitted will vary directly as the area of the opening of the diaphragm; or, if a converging lens is so placed that an image of the bright surface which is the source of light is thrown by it on to the photometer screen, the flux of the beam may be diminished by stopping down the lens, and the intensity will vary very nearly proportionally to the aperture of the diaphragm. The greater thickness of the lens toward the center, as compared with the sides and the possible aberration of the lens, will cause this law to be not quite rigorous, and any such arrangement as this needs to be calibrated by experimentation. With either of these arrangements the diaphragm may be one which can be adjusted continuously, whereby a convenient and effective device is constituted. Ordinarily, the bright surface which constitutes the source of light will be a piece of translucent glass. Ground glass should not be used for this purpose, since it is a very poor diffuser. Some of the other forms of glass, such as alabaster glass, etc., should be used, and it is preferable that the surface of such glass shall be ground as an additional precaution.

The diaphragm principle may also be used in connection with straight-filament incandescent lamps. If the image of the filament is thrown by means of a lens on to an adjustable slit, with the image crossing the jaws of the slit at right angles, the light transmitted by the arrangement will vary directly as the width of the slit.

Any good form of adjustable diaphragm can be used for photometric work. The one most commonly employed is Cornu's "cat's eye," which consists of two metal strips pierced with rectangular openings, and arranged to slide one upon the other in the direction of the diagonal line of the openings. The movement may be pro-

duced by a rack and pinion, or by a micrometer screw, and the position may be read from an attached vernier and scale. The metal strips are illustrated in Fig. 5.

Another available form of diaphragm is the iris diaphragm, which is very commonly used with photographic lenses. The calibration of such a diaphragm is made empirically.

Polarization.* If the light from one source is polarized by passing through a Nicol or other polarizing prism, or by reflection from a pile of glass plates at the angle of polarization (about 56° 20′ for light crown glass), it loses more than one-half of its intensity

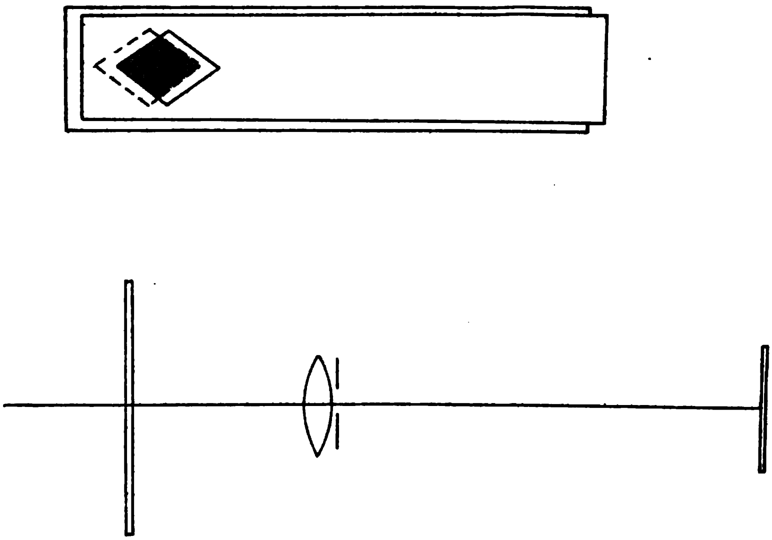

FIG. 5.—Cornu's Cat's Eye.

in the process, and the intensity of the polarized beam may be still further cut down to any extent by means of an analyzer. This analyzer may be a duplicate of the polarizer, or it may be any form of totally polarizing device. When the polarizer and the analyzer are "parallel," the polarized light emerges from the analyzer but little decreased in intensity. When they are "crossed" the beam is entirely extinguished. The intensity of the beam varies as the square of the cosine of the angle of rotation of the analyzer with

* The reader is referred to the subject of polarization in any good text-book of physics.

respect to the polarizer. The method must be used with precaution where there is any possibility that the light which is to be measured is already polarized partially, as for example, light from the sky. The Nicol prism suffers from a further disadvantage of being very expensive in large sizes and absorbing a very considerable percentage of the incident light, thereby producing a dark field. Moreover, its absorption is selective, being very great in the blue and violet end of the spectrum. On account of these disadvantages, and since the required end can usually be attained by simpler means, the polarization method is not very extensively used in photometry.

Absorbing Media. The intensity of a beam of light may be cut down in known ratio by passing it through an absorbing medium. A prime necessity in the case of such media is that they shall be uncolored; that is, that they shall transmit all colors of light equally. This is a condition which is scarcely fulfilled to an exact degree by any medium, but various media are available which are sufficiently colorless for practical purposes. For diminishing the light to a slight degree, a plate of clear glass may be used, or several plates may be piled one on the other. By inclining these plates to the axis of the beam, the amount of diminution may be changed. The diminution in this case is produced chiefly by reflection from the surfaces of the plate. For a glass of known index of refraction, the light reflected on one surface, the incidence being normal, the coefficient of reflection may be computed from Fresnel's equation,

$$m=\left(\frac{n-1}{n+1}\right)^2$$

where n is the index of refraction. For example, with light crown glass having an index of refraction of 1.5, the value of the beam transmitted from the air into the glass normally is 96 per cent of the incident beam. A further reflection of the same percentage of the beam which remains takes place on emerging from the glass into the air, so that the total light transmitted is 96 per cent by 96 per cent, or 92.2 per cent plus such light as is regained by secondary reflection.

Absorbing media may be divided into two important classes. First, those media which permit the beam to pass unaltered, except in intensity; second, those which diffuse the light as well as absorbing it. An example of the first class of absorbing media is

ordinary smoked glass. An object can be seen through a piece of smoked glass without any distortion, only with a diminution of the brightness. An example of the second is a piece of alabaster glass or of thin paper, that is, media which diffuse as well as absorb the light, and which are commonly called translucent. The action of the media of the two classes in photometric apparatus is quite different. A piece of smoked glass can be interposed between a lamp and a photometer at any point in the beam, and will cut down the light incident upon the photometer by a definite amount. If a diffusing glass is used for this purpose, it becomes a secondary

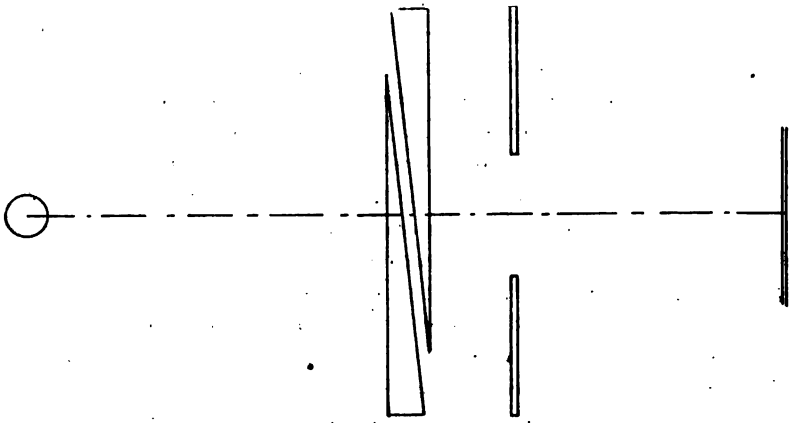

FIG. 6.—Photometric Wedge.

source of light, and the amount of diminution found on the photometer disc differs greatly with the position of the diffusing glass with respect to the disc, and if the glass is stationary on the photometer bar while the photometer is moved, photometric distances must be measured from it rather than from the lamp which is the actual source of light.

The Photometric Wedge. By using a wedge-shaped piece of smoked glass, the intensity of a beam of light can be diminished continuously. This was done formerly by Pickering. An improvement in the photometric wedge was introduced by Spitta,* who used two wedges to slide over each other instead of a single wedge, as illustrated in Fig. 6. With this arrangement, the thickness of the absorbing medium through which the light must pass

* Proceedings of the Royal Society of London, Vol. 47, p. 15, 1889.

can be varied from a lower limit, which depends upon the acuteness of the angle of the wedge and upon the width of the opening in the diaphragm through which the light is allowed to pass, to an upper limit, which is nearly twice the thickness of one wedge. The loss of light in passing through an arrangement of this sort is due to two effects: first, absorption in the wedges; second, reflection from the surfaces of the wedges. The second loss enters in as a constant quantity, superimposed upon the absorption loss, which is proportional to the thickness of the wedge. On this account, and because of inequalities in the glass, it is necessary that wedges should be calibrated throughout their entire range before being used in photometric measurements. The relative position of the wedges may be read from a vernier and scale attached to them.

Another form of graduated absorbing medium has been employed in a portable photometer by Dr. Williams,* who used a photographic film which had been exposed and developed so that it showed a gradually increasing density. Evidently this plan is capable of considerable development. An arrangement of this kind must also be calibrated empirically throughout its length.

Inclined Plate. If the source of light is a diffusely reflecting or transmitting surface, as, for instance, an illuminated surface of plaster of Paris, or a window of diffusing glass, the light which it sends in a given direction may be altered by changing the angle between the normal to the plate and the direction in question. If the diffusing surface is a good one, the diminution of light as the plate is turned from the normal will vary proportionately to the cosine of the angle for considerable angles from the normal. In any case, it is advisable that a plate used in this way should be calibrated empirically.

Varying the Source of Light. In certain apparatus the photometric setting has been made by varying the total amount of light given by the comparison source. With a flame source this may be done by raising and lowering the flame. Then a measurement of the flame height indicates the photometric setting. When an incandescent lamp is used as the comparison source, its intensity may be varied over considerable limits by varying the impressed voltage. This has the disadvantage that the color of the light varies at the same time. The first of the above methods is adapted to only the roughest kind of work.

* Transactions Illuminating Engineering Society, p. 540, 1907.

PHOTOMETERS

Principles

In the fields of photometric sight boxes two principles are made use of. First, is the equality principle. In photometers intended to employ this principle the fields are so constructed that the eye compares their brightness directly, and endeavors to tell when they are equally bright. It is very difficult to do this with any degree of accuracy unless the fields are so arranged that the dividing line between them disappears when the equality point has been reached. Hence, such photometers are called also "disappearance" photometers. Then the eye, by observing the merging of one field into another, can determine the point of equality with considerable accuracy. Second, is the contrast principle. In accordance with this principle, each field consists of two parts: first, a part illuminated by its own proper source; second, a part illuminated by the other source, but to a different degree. With this arrangement equality exists when the contrast in the right-hand field between the portions of the field illuminated by source A and source B is the same as the contrast in the left-hand field between the portions illuminated by source B and source A. If the degree of contrast is the correct one, the eye is able to determine this equality of contrasts with great precision.

In photometers using the contrast principle, the equality principle may also be employed, since when the equality of contrast is established equality of illumination is also observed. If, when equality of illumination is observed, exact equality of contrast is not observed the construction of the apparatus is faulty. The degree of contrast which gives the most sensitive arrangement depends to some extent upon the illumination of the fields. The contrast must appear in all cases quite small. Since the ability of the eye to distinguish a contrast varies with the brightness of the field, a smaller contrast should be employed with a photometer used with very bright fields than with one where the fields are only faintly illuminated. As a practical matter, a contrast of about 8 per cent between the two portions of the field seems to give in a general case the most satisfactory results.

A great variety of photometers have been constructed, embodying the above principles, and other variations are possible. At the present time only a few of the varieties are of much practical

importance, so that while some of the older kinds should be mentioned as being of interest and of use in certain special cases, particular attention will be given to the description of those forms which have proved themselves to be of the greatest practical importance.

Lambert's Photometer. This photometer, of which Rumford's photometer is a modification, dates from the middle of the 18th century. The opaque screen HI (Fig. 7) is so arranged before the white screen BCEG that a certain region to the right of the line DF is illuminated only by the source L, while a region to the left of the line is illuminated only by L′. When the two fields are

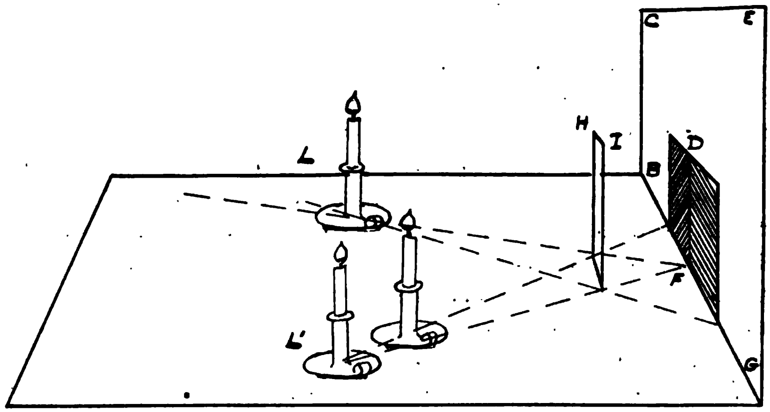

FIG. 7.—Lambert's Photometer.

made equal by adjusting the distances of the lights, the line of separation along DF disappears, and the two fields merge into one. In order not to introduce any error due to difference in obliquity of incidence, the angles of incidence must be equal.

Bouguer's Photometer differs from Lambert's in that the opaque screen dividing the fields is placed perpendicular to the illuminated screen, as is shown in Fig. 8.

Foucault's Photometer differs from that of Bouguer in that the screen SS′ is of translucent diffusing material, such as a layer of fine-grained precipitated starch between plates of glass, and the fields are viewed from the far side. The screen HI is made movable lengthwise so that the edges of the fields can be made exactly to touch each other. When the fields are equal, the line of separation along I vanishes. The screen is viewed either through a

simple tube or through a telescope. The sight box is placed at the junction of two tracks meeting at an acute angle, along which the lights can be moved.

Harcourt's Table Photometer, as adopted by the London Gas Referees, is a modified form of Foucault photometer. The separating screen at right angles to the diffusing screen is, however, replaced by

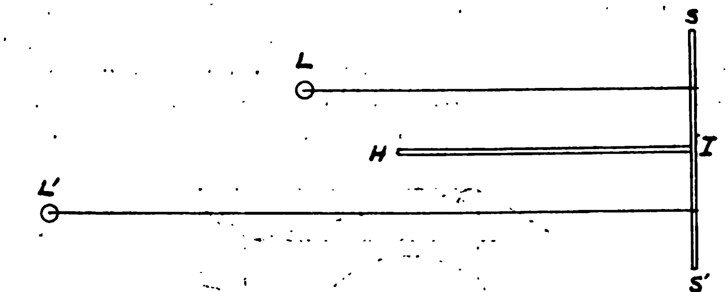

FIG. 8.—Bouguer's Photometer.

an opaque screen set at a little distance from the diffusing screen and parallel with it. In the opaque screen is a square hole. The two sources of light shining through this opening throw bright spots on the diffusing screen. The screen is so adjusted that these spots are made to touch each other. The equality of brightness of these two spots is observed looking from the rear side of the diffusing screen.

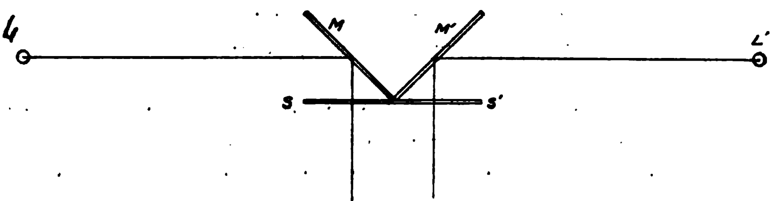

FIG. 9.—Ritchie's Wedge Mirrors.

Ritchie's Photometer has two mirrors M and M′ (Fig. 9) which throw the light from the two sources upon the translucent screen SS′. This sight box is mounted on a track between the lights, and is moved along until equality of illumination is secured.

Nichols has modified this photometer by arranging the mirrors to cross at their mid-points (Fig. 10), one above the other. The illuminated fields are thus seen one above the other, instead of side by side as in in the original form.

Ritchie's Wedge Photometer. This differs from the form described above in that the screen SS′ is removed, and for the mirrors are substituted pieces of white cardboard with unglazed surfaces. When a setting is secured with lights of the same tints the line of separation between the cardboards disappears, provided that it is a sharp one. Various modifications of this photometer have been described. If the wedge is made of plaster of Paris, and the edge of it is made very sharp, the photometer is said to give very good results. Unless the wedge is placed directly perpendicular to the track, the wedge photometer is subject to an error due to the unequal obliquity of the surfaces with respect to the

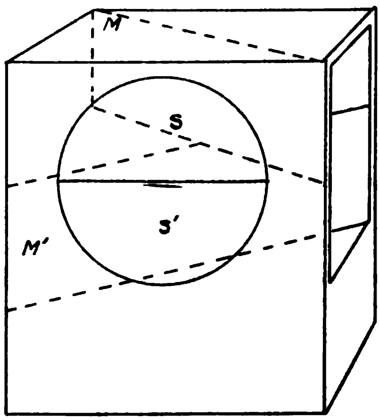

FIG. 10.—Nichols' Crossed Mirrors.

axis of the photometer bar. A small variation from the proper position of the wedge may produce an error of noticeable dimensions because the effect of a variation is to increase the obliquity of the light on one side of the wedge and to decrease it on the other, thereby producing a double effect. Moreover, the angle of the wedge is of such a value that the cosine is varying rapidly. Since the illumination of the plate also varies with the cosine of the angle according to Lambert's law, this condition is such that a small variation in the position of the wedge will produce a relatively large error in the result.

Elster-Joly Block. This simple photometer has been constructed in a variety of ways, all in accordance with the same principle. Two blocks of translucent substance, such as paraffine or milk-

glass, are placed either side by side or one over the other in such a way that each receives the light from one of the lamps. For instance, if they are placed side by side, a very thin metallic diaphragm may be placed between them. When viewed from the front each block is seen illuminated by the internally diffused light from its respective lamp, and the equality of brightness is readily observed.

Bunsen Photometer. This is one of the most common and the most practical form of photometer in use at the present day. The photometer is capable of considerable variations in the manner of its construction and use, the principle involved being always the same. The theory of it may be outlined as follows: Suppose a piece of white paper, a portion of which has been rendered translucent by a drop of grease or of wax, is held between two sources of light which are to be compared.

If an observer looks at the right side of the paper while holding it in such a position that the illumination of the paper due to the source at the right is considerably greater than that due to the source at the left, he will see the grease spot as a dark spot on a light background. If the paper be held so that the illumination due to the source at the left is enough greater, the grease spot will appear bright on a darker background. At some intermediate point, consequently, the spot, being neither brighter nor darker than its background, will disappear altogether, unless the quality or color of the light coming from the greased portion is different from that coming from the ungreased portion. If this difference in quality is but small, the point of equal illumination of the two parts of the screen can be determined with considerable nicety.

This point does not in general represent, however, the position of equality of illumination on opposite sides of the disc, for if the observer makes a similar setting while looking at the left-hand side of the disc, a different point of disappearance of the spot will be found. This is due to the fact that the amount of light lost by absorption in the greased portion is different from that in the ungreased portion, and to the different diffusing powers of the greased and the ungreased portions. The true photometric setting can, however, be deduced from a pair of observations such as the above. If we designate by r_1 and r_2 the distances to the respective sources when the setting has been made, while observing the side of the disc which is turned toward the source of intensity

I_1, and by r_1' and r_2' similar quantities when the disc has been reversed and the same side of it is observed turned toward the source of intensity I_2, then,

$$I_1 = \frac{r_1 r_1'}{r_2 r_2'} I_2$$

For, designating by ρ_1 and t_1 the coefficients of reflection and transmission of the ungreased portion of the disc, and by ρ_2 and t_2 the same for the greased portion, the condition that the brightness of both parts shall be equal when viewed from the side turned toward I_1, or that the line of demarkation shall disappear, is expressed by the equation

$$\rho_1 \frac{I_1}{r_1^2} + t_1 \frac{I_2}{r_2^2} = \rho_2 \frac{I_1}{r_1^2} + t_2 \frac{I_2}{r_2^2}.$$

Similarly, when the disc is reversed and the same side is again observed,

$$\rho_1 \frac{I_2}{r_2'^2} + t_1 \frac{I_1}{r_1'^2} = \rho_2 \frac{I_2}{r_2'^2} + t_2 \frac{I_1}{r_1'^2}$$

These equations yield the following values of I:

$$I_1 = \frac{t_2 - t_1}{\rho_1 - \rho_2} \frac{r_1^2}{r_2^2} I_2,$$

$$I_1 = \frac{\rho_2 - \rho_1}{t_1 - t_2} \frac{r_1'^2}{t_2'^2} I_2.$$

Multiplying these equations together and extracting the square-root of the product, we have, as above,

$$I_1 = \frac{r_1 r_1'}{r_2 r_2'} I_2.$$

The equations become more complicated in case the disc is not reversed for the setting to right and left, since the coefficients ρ and t are usually different on opposite sides of the same disc.

Evidently the Bunsen photometer can be used without reversal if the substitution method be followed. In this case the ratio of the intensities of the lights is given directly as the squares of the distances.

The Bunsen as a Contrast Photometer

It is far more common, as well as far better practice, in the use of the Bunsen photometer to observe both sides of the disc simultaneously by the aid of a proper arrangement for the purpose. When this is done, the observer sees a contrast between the greased and ungreased portion of the disc; that is to say, with a given

illumination, the brightness of the greased and ungreased portions will not be the same. The photometer is adjusted on its bar until the contrast between the greased and ungreased portions is the same on one side as on the other. So used, the Bunsen photometer becomes a contrast photometer, and is much more sensitive than when used as a disappearance instrument.

The opposite sides of the disc will usually have slightly different optical properties, so that it is necessary, in order to get a true setting by the direct-comparison method of photometry to take readings with the disc direct and reversed. If the disc is a good one, the readings in the two positions will lie very close to each other, and the mean position, as obtained by averaging, may be taken as the correct setting of the photometer. If the positions do not lie close together, the equation for computing the candle-power of the unknown source of light is the same as that given above for the Bunsen disc used as a disappearance photometer, namely,

$$I = \frac{r_1 r_1'}{r_2 r_2'} I_2.$$

The derivation of this equation for the contrast method is analogous to its derivation as given above for the disappearance method. The complication of reversal may be avoided by using the substitution method.

Construction of Discs. The method employed in constructing the disc has a great influence not only on its sensitiveness, but also on the accuracy of the results obtained by its use. Three conditions must be fulfilled by a good disc; 1, the two sides must be alike; 2, the contrast between the greased and ungreased portions must be such as to give the proper degree of sensitiveness for the work in hand; 3, the paper and the grease must exercise no selective reflection or absorption on the light. It is a matter of great difficulty to secure uniform discs. If the paraffine or stearine, which are the materials commonly employed in making the spot, are in excess on the surface the properties of the disc may be materially changed by changing the degree of polish on the surface of the wax. The degree of contrast obtained varies greatly with the amount of wax which the paper has absorbed.

Various procedures have been recommended for constructing discs. A piece of copper, round- or star-shaped, as it is desired that the disc shall be, may be plunged into a bath of the molten

wax, held there until it is thoroughly warmed, and then pressed on the paper until the wax has completely penetrated it. The excess of wax should be removed by scraping or by laying on a piece of blotting paper and pressing with a hot iron. Another way is to clamp the paper between pieces of metal having apertures of the shape that the spot is to assume, and to dip the whole into the molten wax. Two equal cylindrical pieces of metal may be employed, in which case the disc has an opaque center and a translucent margin. After scraping off the excess of wax, the disc so prepared may be placed in a steam or a warm-air bath until the distribution of the wax has become uniform; very good discs can be made in this way.

Heavy, unsized white paper should be used. White drawing paper makes good discs.

The Leeson Disc. This is a built-up disc, made by pasting sheets of thin, translucent paper to each side of a piece of heavy paper in which an aperture, in the form usually of a slender-pointed star, has been cut. The inner paper may be the same as is used in the construction of grease-spot discs. The outer paper is selected to give the right degree of contrast, and should have an unglazed surface. Thin starch paste may be used, care being taken that the outer sheets adhere to each other over the entire portion where the middle paper is cut away, particularly in the points of the star. The outside and the middle papers should be wetted before the paste is applied, and the excess of water removed by pressing between cloths. After pasting, the disc should be clamped tightly between blotting paper in a letter press, where it is allowed to remain until it is thoroughly dry. Such a disc is sometimes mounted between sheets of clear, white glass, which protect it from dust and counteract any tendency to buckle out of shape. This disc possesses the advantage that its surface is everywhere of the same texture, and that the desired degree of contrast can be obtained by properly selecting the materials. It is also much easier to secure a good degree of uniformity in making these discs than in the case of the grease-spot disc.

Selection of Discs. Bunsen photometer discs differ in sensibility far more than is commonly recognized, hence it is important to make a careful selection of the disc which is to be used. A sensitive disc is one which will show a marked change in appearance for a small change in the illumination on either side. If the pho-

tometer is set at a balance, a small motion to one side will cause one of the spots to disappear, and a small motion to the other side will cause the other spot to disappear. The distance between these two disappearance points may be taken as characterizing the disc. In a sensitive disc this distance will be small. In an insensitive disc it may be very considerable indeed.

Bunsen discs are divided into two classes; that is, positive discs and negative discs. In the positive disc, at the position of balance, the more translucent portion of the disc appears bright upon a darker background. In a negative disc the reverse is true. With a positive disc, disappearance of the spot on the right side of the disc is obtained by moving the photometer toward the right. With

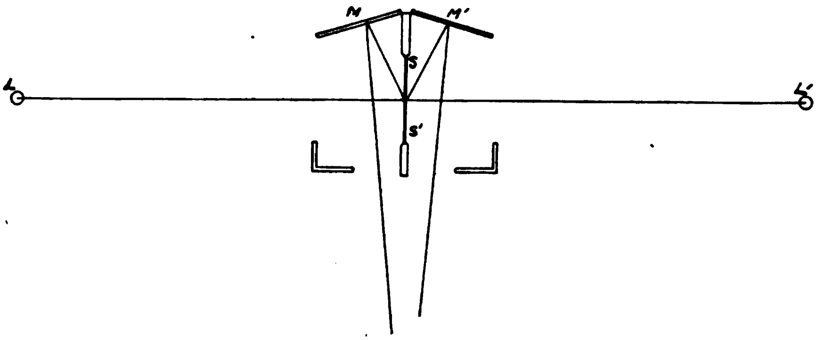

FIG. 11.—Bunsen Photometer with Rüdorff Mirrors.

a negative disc the opposite condition obtains. By proper selection of papers, built-up discs can readily be made of either the positive or negative variety. The positive variety results when the diffusing power of the thin paper is large as compared with its absorption. The negative variety results when the diffusing power of the thin paper is less marked, or when the reflecting power of the thick paper used is high as compared with that of the thin paper. The proper selection of materials for built-up discs is a matter of great importance in determining the sensitiveness of the discs produced.

Rüdorff Mirrors. These mirrors constitute a simple device, which is in almost universal use, for enabling the two sides of the Bunsen disc to be seen simultaneously. It consists in a pair of mirrors placed vertically behind the disc and inclined at an angle of about 140° to each other. The intersection of the mirrors lies

in the plane of the disc. By looking into the mirrors, two images of the disc are seen rather close together, and the eye, by glancing quickly from one to the other, can compare them very readily. The mirrors themselves should be cut from the same piece of glass. They, together with the disc, are mounted in a small box which is cut away at the sides to admit the light, and in front to permit the screen to be seen, as shown in Fig. 11. The box should be painted dead black within and without, and is fixed on a carriage in such a way that it can readily be reversed.

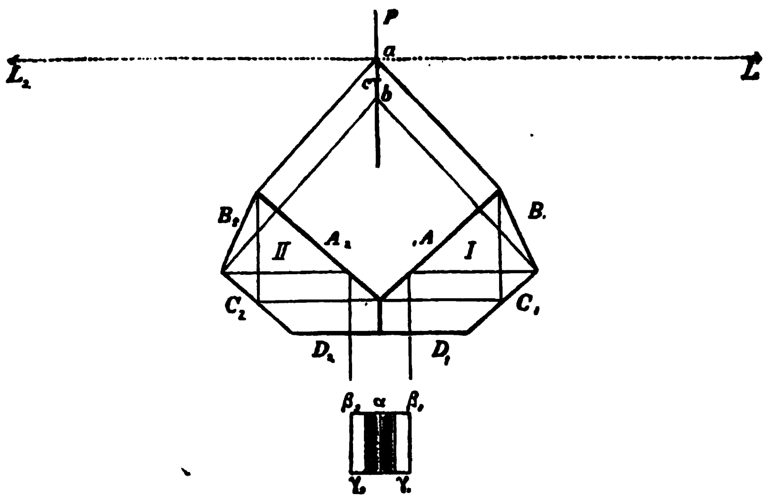

FIG. 12.—Krüss Prisms.

Krüss Prisms. The disc p (Fig. 12) is greased along a vertical line of width ac. The light from the disc, after total reflection inside the prisms ABCD, emerges in a direction at right angles to the disc, and the latter is seen as shown at the bottom of the figure, the two images of the greased portion meeting each other sharply in a line.

Sources of Error. It rarely happens that a disc has exactly the same optical properties on both sides. Even if a disc is perfect in this respect when first made, the adhesion of dust and slow chemical changes are likely to produce differences in the course of time. As a consequence, it is necessary when comparing lights by the direct rather than the substitution method to reverse the sight box, making an equal number of settings in either position.

The differences between the sides of a disc may be very large, and the neglect of this precaution may lead to serious errors.

Reference has been made above to the discrepancies in the indications of discs due to differences in the thickness of the wax in the spot and to the nature of its surface.

Nichols * has studied another source of error in the use of the Bunsen photometer with Rüdorff mirrors. He found that different observers would set the photometer persistently to the right or to the left of its true position, and that the sign of this deviation changed when observations were made by the aid of a mirror with the back of the observer turned towards the photometer, or when the observer worked from the other side of the track. The deviations became zero when the observers worked with one eye covered. The magnitude of this error was in one case 8.7 per cent. The effect is to be ascribed to differences in the eyes of the observer, and it may be largely avoided by holding the head at a considerable distance from the disc, so that both eyes act as one, or by the use of Krüss † prisms which are illustrated in Fig. 25.

This error is only an exaggerated form of the one-sidedness error which is noticed in the case of practically all observers on any kind of photometer. The use of the substitution method eliminates the above errors in the case of practiced observers who have acquired a fixed habit of observation.

Lummer-Brodhun ‡ Photometer. This is one of the most sensitive and practical photometers known, and is very extensively used, both for precision and for technical photometric work. It is made both in the form of an equality photometer and a contrast photometer, the latter being the more sensitive device. A scheme of the photometer is shown in Fig. 13. In this figure S is an opaque diffusing screen, for example, of plaster of Paris, the oppo-

* Transactions American Institute of Electrical Engineers, 1889.

† Journal für Gasbeleuchtung und Wasserversorgung. Vol. 27, p. 587, 1884.

‡ It has been pointed out by Prof. Knott in the Philosophical Magazine, Vol. 49, p. 118, 1900, that a prism combination practically identical with the Lummer-Brodhun prism was constructed by Prof. Swan of the University of Edinburgh and described by him in the Transactions of the Royal Society of Edinburgh, Vol. 22, 1859. Prof. Swan used his prism pair in photometric work for many years. In the application of the *contrast* principle to such a prism combination, Lummer and Brodhun may undoubtedly claim priority.

site sides of which are illuminated by the sources of light which are to be compared. At M and M′ are two mirrors. Next in the train is the essential part of the instrument, namely, the Lummer-Brodhun photometer prism or cube. This consists of two right-angle prisms. The prism GFH has the outer portions of its hypothenuse face ground away, leaving only a small circular portion ED in the center plane. These prisms are clamped in a metal holder, by which they are pressed together so tightly that all air is excluded from between the surfaces limited by ED. Consequently, over this small circular area the two prisms become optically homogeneous, and light will pass through one to the other

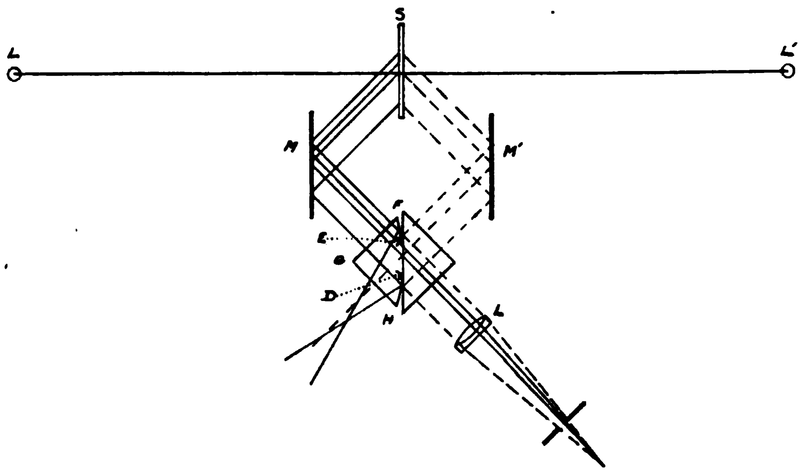

FIG. 13.—Lummer-Brodhun Photometer.

without diminution. The lens L is placed as a magnifying glass for viewing the hypothenuse surfaces of the prisms. The action is as follows:

Light diffusely reflected from the left-hand side of S is further reflected by M and enters the surface GF of the left-hand prism. Those portions of this beam of light which fall upon the surface ED are transmitted thereby and proceed through the second prism to the lens L, and so to the eye. Those portions, however, which reach the surfaces FE and DH are totally reflected and do not pass into the second prism. Similarly, the light from the right-hand side of S falling upon M′ is thereby reflected into the right-hand prism. Those portions of this light which fall upon ED

are transmitted and do not reach the lens L, whereas the light falling upon the surface FEDH is totally reflected and is directed toward L and toward the eye. The eye, therefore, when accommodated upon the surface FH sees a circle ED, apparently of the same brightness as the left-hand side of S, and surrounding that circle and fitting it exactly, a ring of the same brightness as the right side of S.

When the sides of S are equally illuminated, the field of the photometer shows everywhere the same brightness, and the line of separation between the ring and the disc disappears, provided that the lights are of the same color. If the lights are of different

FIG. 14.—Lummer-Brodhun Photometer.

colors, the two portions of the field will always be distinct, but at the point of equality can still be determined with a certain degree of accuracy, although settings made under these conditions are much more difficult to make and are far less accurate than when the colors are alike.

The Lummer-Brodhun prism is used in many forms of photometric apparatus. The standard form for use on the bar photometer is illustrated in Fig. 14, in which the various portions of the apparatus are clearly visible. The box is made reversible so that inequalities of the two sides can be cancelled out. The equation for computing the candle-power is the same as in the case of the Bunsen contrast photometer.

The photometer box is obtainable also equipped with a divided circle, whereby it can be set to any required angle with the vertical, an arrangement which is convenient for some classes of work. It may also be had with an extra prism, whereby the sight tube of the photometer is brought out perpendicular to the photometer track. In Krüss's construction the perpendicular sight tube is axial with the box. In the Schmidt & Haensch construction it is parallel with the axis of the box, but slightly to one side of the same. Whether these constructions are preferable or not is largely a matter of personal opinion.

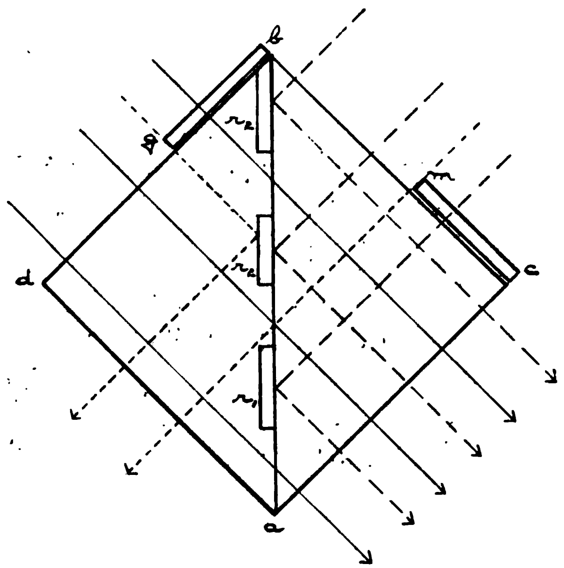

FIG. 15.

Lummer-Brodhun Contrast Prism. The contrast prism is illustrated in Figs. 15 and 16. The portions r_1 and r_2 of the prism ABD (Fig. 15) are etched, the portion r_1 being cut in the form of r_1 in Fig. 16, and the form r_2 as shown at r_2 in Fig. 16. GB and MC represent pieces of plane-parallel clear glass which are affixed to the prisms, as shown, and which serve the purpose of producing a diminution of about 8 per cent in the intensity of the light which traverses them. The result is that the portion of the field l_2 is illuminated from the left-hand side of the screen to the full value, while interposed in the field l_2 is the smaller field r_1,

which is illuminated from the right side of the screen to a slightly diminished value, the diminution being caused by the absorption of the glass MC. Similarly, the portions of the field r_2 are illuminated from the right side of the screen to the full value, and interposed in this field is the smaller field l_1 illuminated from the left side of the screen to the diminished value. When the illuminations on both sides of the screen are equal, the brightness of the field l_2 is the same as the brightness of the field r_2, and the field r_1 makes the same contrast with the field l_2 that the field l_1 does with the field r_2. Hence, the photometer may be used by noting the disappearance of the vertical lines between l_2 and r_2, in which case it is an equality photometer, or it may be used by making the con-

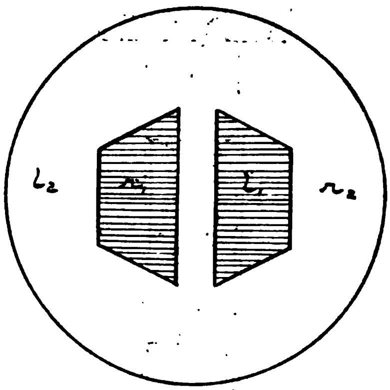

FIG. 16.

trast between r_1 and l_2 the same as l_1 and r_2, in which case it is a contrast photometer. In other makes the smaller fields r_1 and l_1 are given in a different form from that herewith shown.

Sensitiveness. Since the eye is able to perceive a smaller degree of difference in contrast than difference in brightness, the contrast form of the photometer is more sensitive than the disappearance form. As a disappearance photometer the Lummer-Brodhun fulfils the requirements that each portion of the field must be illuminated solely by the light from one source, and that there shall be no mixing of the illumination. With the Bunsen disc the brightness of the translucent part of the disc is due partly to light reflected from one source and partly to light transmitted from the other source, hence it follows that if the photometer is slightly

displaced from the position where a true setting would be made, the contrast between the two portions of the field is less with the Bunsen than with the Lummer-Brodhun screen under the same conditions. On this account the Lummer-Brodhun is more sensitive than the Bunsen as a disappearance photometer. Used as a contrast photometer the Lummer-Brodhun shows the same theoretical superiority over the Bunsen screen, since each portion of the field is illuminated by light proper to one source alone. It

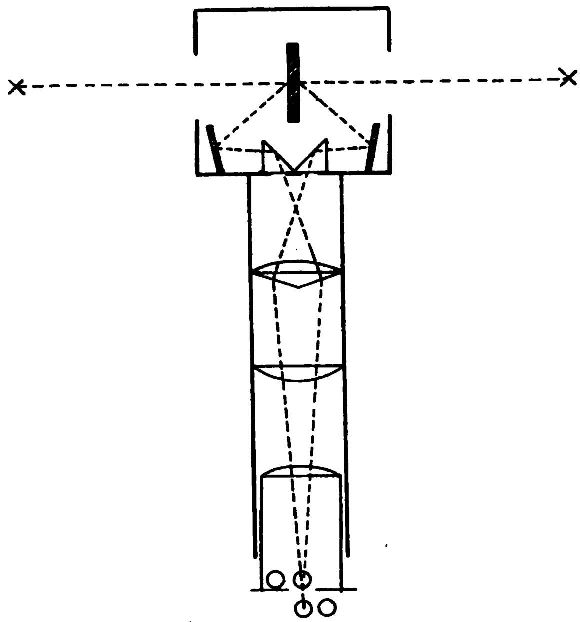

FIG. 17.—Marten's Photometer.

should not be concluded from this, however, that in all cases the Lummer-Brodhun is more sensitive than the Bunsen. Observers with the Bunsen photometer become, as a result of long practice, very expert in its use, and are capable of getting surprisingly close results. Moreover, the Bunsen photometer, especially with the star disc, is considerably easier to use with a difference in color between the lights than is the Lummer-Brodhun.

The Martens Photometer. A view of this photometer, as constructed by Franz Schmidt & Haensch, is shown in Fig. 17. A diffusely illuminating screen sends light by way of mirrors and

reflecting prisms to a bi-prism, which is fastened to one face of a plano-convex lens. In looking at the surface of this prism through the other lenses of the arrangement, one side 2 is seen illuminated by the light from the right-hand side of the screen, and the other surface by light from the left-hand side of the screen. Upon bringing the brightness of the two sides of the screen to equality, the line of division between the sides of the bi-prism disappears. This, therefore, makes a form of disappearance photometer which belongs optically to the same class as the Lummer-Brodhun, and which is somewhat less cumbersome as to size and weight, but which on account of the narrow aperture of the ocular diaphragm is somewhat less convenient to use. This photometer is also made as a contrast photometer.

Practical Apparatus

The Precision Bar Photometer. For precise work, a bar photometer, suitably equipped, constitutes unquestionably the best form of apparatus. As ordinarily used, the lamps to be compared are set up at a given distance apart at the ends of a bar or track on which moves a carriage carrying the photometer head. The bar should be straight and level and free from flexure. The carriage or carriages which ride upon it should move with perfect freedom, but at the same time without any side play. In other words, the construction should be such that in moving from one end of the bar to the other the center of the photometer disc should at all times lie in the photometric axis, and the disc itself should at all times be at right angles to the photometric axis. By photometric axis is meant the line joining the lamps and lying parallel with the bar.

The lamps to be measured may be supported either by carriages rolling on the bar or on fixed supports at a given distance from the end of the actual track. The supports for the lamps should have a vertical adjustment so that the axis of the lamps can be brought to the proper height, and the carriages should also have a vertical adjustment to bring the objects which they carry into the same horizontal line. Clamps should be provided whereby the carriages can be securely locked to the track at any required point.

Screening. A most important consideration in the arrangement of any photometer is proper screening of the light. It is imperative that no stray light should reach the photometer disc, and that

its illumination should be due solely to the light radiated directly by the lamps alone. Hence, the background of the lamp is important. Sometimes a black-velvet surface is placed behind the lamps to serve as a background. This is very efficient as long as it is clean, but black velvet readily collects dust and may, when sufficiently coated, reflect an amount of light which should be taken into consideration. If the ends of the room in which the photometer is placed are painted black, and are sufficiently distant from the lamps so that the illumination which they receive is very feeble, no other background is necessary.

Between the lamps and the photometer head should be placed a series of black screens. These screens should have apertures of varying sizes, the largest openings being in the screens nearest the lamps, and the smallest ones in the screens near the photometer head, and very little larger than the openings in the photometer box. These screens should be sufficiently numerous, and should be so spaced that the eye, when placed at the position of the photometer disc and looking along the bar, can see nothing but the surface of the screens and the background at the end of the bar. The walls of the room should be entirely hidden within the angle at which it is possible for light to enter the photometer box and reach the photometer screen. The dimensions should be so arranged that the light from the lamp at one end of the bar cannot illuminate any of the screens on the opposite ends of the bar so as to reflect light on to the photometer disc. When all these precautions are taken, the screens will be sufficiently black if they are painted with a good dull, black paint, and all danger of error due to stray light on the photometer disc is avoided. It is important, however, to arrange the screens so that the observer at the photometer shall not receive any of the light of the lamps in his eyes. It is desirable in the interests of sensitiveness, accuracy in observation and of the avoidance of stray light that the walls of the photometer room should be painted dull black. It is particularly important to avoid placing in the beam of light any surfaces which may receive light at large angles of incidence and reflect it on to the photometer disc.

Some of the screens may advantageously be attached to a frame carried by the photometer carriage. If three or four screens are placed on each side of the photometer carriage in this way, very effective screening results. The screens should be made of thin

material, so as to avoid the error mentioned above of reflection at sharp angles, or if they are not of thin material the material around the apertures should be chamfered off to a thin edge which can reflect no light. Many photometrists have fallen into serious error due to neglect of the simple precautions regarding screening which are indicated above.

Scales. The scale on the photometer bar should be preferably made with white lines and figures on a black background, and a convenient arrangement should be provided for illuminating it when it is to be read. The division of the scale may be either

FIG. 18.—Bureau of Standards Photometer Bar.

equal part, proportional or direct reading. An equal-part scale divides the total distance between the lights into a certain number of equal divisions. The length of the divisions may be purely arbitrary, but it is convenient to have the total number of divisions 1000. The results of the photometric measurement must be computed according to the inverse square law.

The proportional-part scale is divided to give the ratio of the candle-power of the lamps at the two ends of the bar. Unity comes at the center, and the readings of a scale of this sort must be multiplied by the candle-power of the standard in order to give the candle-power of the unknown lamp.

A direct-reading scale is one which reads the candle-power directly. It is a proportional scale in which the proportionality numbers are already multiplied by the candle-power of the standard with which the bar is intended to be used. While a direct-reading scale on an ordinary photometer reads candle-power, on an illumination photometer it may be calibrated to read directly in units of illumination.

The most commonly used type of precision photometer bar is the Reichsanstalt type, in which the tracks are of circular cross-section, either of steel tubing or of cold-rolled shafting, about 1

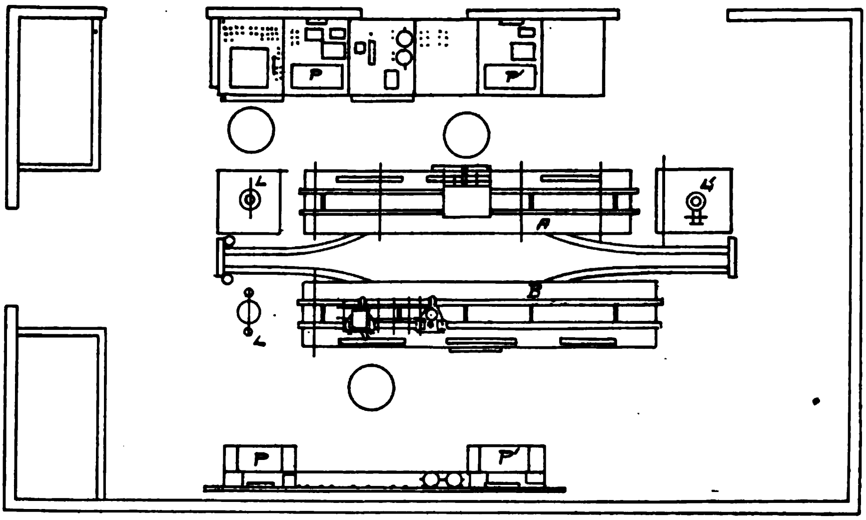

FIG. 19.—E. T. L. Standard Photometer Room.

inch in diameter, and the carriages run on three wheels, two of which are spool-shaped so that they fit perfectly on the track at all points without side play.

As an illustration of precision photometric apparatus, the photometer bar with its auxiliaries used at the Bureau of Standards in Washington, and shown in Fig. 18, may be cited.

The bar is of the Reichsanstalt pattern, 3 meters in length, and is equipped with a Lummer-Brodhun contrast photometer. Numerous screens are provided, as seen, so that stray light is effectually excluded from the photometer disc. The lamp to be measured is enclosed in a cylindrical screen and is affixed to a carriage which

is seen near the left-hand end of the bar. The comparison lamp, at the right-hand end of the bar is also supported on a carriage which is connected by a rigid rod to the carriage on which the photometer head is placed. A rotating sector disc is also seen on the photometer bar. This disc can be placed on either side of the photometer head, and is used for cutting down the intensity of either light in a fixed ratio. The measurements of voltage and current are made by means of a potentiometer, the galvanometer of which is seen attached to the wall, so that the spot is thrown on a translucent screen directly in front of the photometer.

A further illustration is furnished by the standard photometers of the Electrical Testing Laboratories. Two such photometers are placed back to back in a room about 12 feet by 30 feet (Fig.

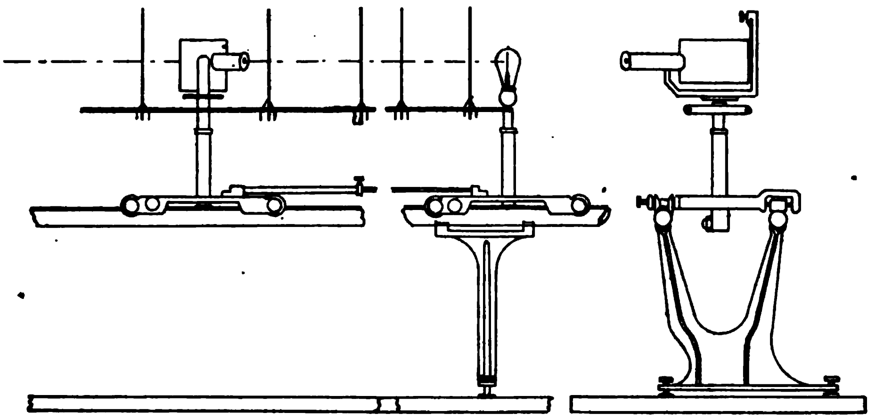

FIG. 20.—E. T. L. Standard Photometer Supports.

19), with a high ceiling, which is set apart for standard photometer work, and the walls of which are painted black. The photometers, while similar in many particulars, differ in certain details. Both bars are of the Reichsanstalt pattern, but that of photometer B has a modified form of supports, shown in Fig. 20. The carriages also have been designed with particular care to make them mechanically perfect. To minimize the effect of slight irregularities in the track in tilting the photometer head, and thus displacing its center line from a position directly over the index mark, the distance between the horizontal wheels of the carriages of this bar has been made greater than usual. A set of screens

is attached to the photometer carriage and move with it. Other screens are placed on the bar as required. This bar is especially intended for use with the working standard lamp at a fixed distance from the photometer disc. This distance is fixed by rods and can be adjusted as required, so as to bring the illumination on the working standard side of the photometer to a given and definite value, a procedure which is useful in order to make the photometer direct reading. In photometer A, which is used ordinarily with the moving photometer head and a fixed distance between lights, the actual lamps L and L′ are placed on small separate tables and not on the bar. These tables are bolted securely to the floor in such positions that the lamps come exactly 5 meters from each other. The bar being graduated over a range of 3 meters, each lamp is placed 1 meter distant from the end of the graduations. The true position of these lamps is indicated by a pair of plumb-bobs at each end of the bar, the plane of the plumb-lines being at right angles to the bar. With this arrangement the entire length of the photometer track is available for the movement of the photometer head.

Several tables for lamps are provided. One of these is equipped with a universal lamp rotator; another with the mirror form of universal lamp rotator; a third has a simple rotator with four mercury cups for contact, and a fourth is designed to carry a 10-candle-power pentane standard lamp, or some other source of light as required. One table with its equipment can be removed from its position at the end of the bar and another placed in its stead, and bolted to the floor at exactly the proper distance with very little trouble.

The dimensions of the room are such that a greater distance between lights than 5 meters can be had if desired by simply moving the lamp tables farther apart. Where a shorter effective photometer bar is required the lamp can be mounted on a moving carriage on the track, as is done at the Bureau of Standards. This arrangement, then, has the advantage of very great flexibility, which is obtained at no expense of accuracy. Two scales are attached to the photometer bar. One of these is divided into half centimeters, thus making a thousand-part scale when the lamps are 5 meters apart. The other is a proportional scale, corresponding to this distance, having unity at the center of the bar. Photometer B has also two scales, the proportional scale being grad-

uated for a fixed distance between the photometer head and the working standard.

The essential details of the electrical measuring arrangements of this photometer room are as follows:

Against the wall of the room is placed a wooden table carrying switches and rheostats, and all of the electrical measuring apparatus. At one end of the table, near the right-hand end of the bar, is a potentiometer P and equipment for the measurement of the voltage on an incandescent lamp. Near the other end of the table, which comes near the photometrist's position on the bar, is another potentiometer P′ for measuring the current. Simultaneous measurements of voltage and current can be made by two observers. The observer who measures the voltage has also to put lamps in position on the photometer. The other observer who measures current is the one who actually makes the photometric settings. The galvanometers are overhead and throw the spot of light on to scales over the potentiometer table. The arrangement is designed with a view to minimizing errors in electrical measurement due to current leaks, etc. The voltage on either lamp can be controlled either from the measuring table or by the photometrist standing at the photometer bar.

Industrial Photometers

Photometers for Incandescent Lamps. The type of photometer used by the Electrical Testing Laboratories in industrial work is illustrated schematically in Fig. 21, which may be taken as representative of its class. The apparatus is supported on a table about 9 feet in length and 3 feet high. The distance between lights is 100 inches (about 2.5 meters). The central portion of the table is occupied by a box, open in front, which contains the photometer track T, the photometer sight box P, and the reading scale S. It is intended that the photometer shall be used by two operators, one of whom makes the photometer settings and reads the indications of an ammeter connected in the lamp circuit, and the other of whom manipulates the lamps which are being measured and reads the voltmeter. The scale S is read by the photometer setter. As a check on the readings by this operator the scale S′, graduated similar to S, may be read by the other operator. This scale is etched or painted on a steel tape attached to the sight box and running over the pulley A. The tape is kept taut by a spiral

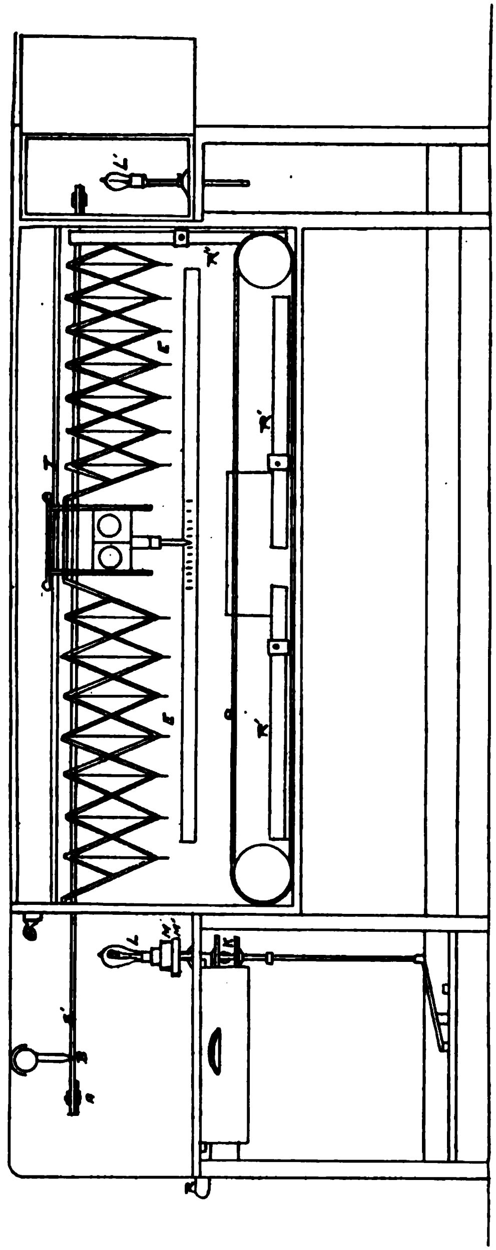

Fig. 21.—Photometer for Testing Incandescent Lamps.

spring and is read from the pointer B. In order that the operator may move the sight box with a minimum of inconvenience, cords run from it over pulleys which can be manipulated by an endless belt C, passing along the entire front of the photometer. The comparison, or working standard lamp, is placed on its support at L′ and is boxed in. The primary standard lamp, or the lamp to be tested, is placed on the rotator at L. The rotator is driven by means of a belt through a clutch operated by a treadle on the floor. By means of the clutch, the rotator can be thrown out or the direction of its rotation can be reversed. The reversal feature facilitates screwing lamps in and out of the socket. Current is carried to the rotator socket by means of mercury cups M and M′. Potential leads are also brought from these mercury cups or from nearby positions on heavy wires leading to the mercury cups. These connections need to be made with very great care, so that the voltage indicated by the voltmeter will be as closely as possible the same as the voltage actually applied to the leads of the lamp. In series with the lamp L are placed the two slide-wire rheostats R and R′, the one being intended for the use of the operator who handles the lamps and the other for the photometrist. A quick-throw switch is introduced into the lamp circuit, by means of which L is thrown out of the circuit and another similar lamp is substituted for it, so that the load upon the storage battery is kept practically constant, and interference of photometers with each other due to voltage fluctuations is avoided. The voltmeter wiring may be so arranged that the voltage on either the test lamp or the substitute lamp is always impressed on the voltmeter, whereby the needle of the voltmeter is not allowed to return violently to zero on removing the test lamp, and is used always heated to its maximum temperature. The slide-wire rheostat R′ is in series with the lamp L′. The voltmeter, which is of the large or laboratory standard type, is enclosed in the drawer which is seen at the left-hand end of the photometer and is seen through a cover of plate glass. Potential leads are brought from between L and L′ to a quick-throw switch placed near the voltmeter, by means of which the voltage on either lamp can be read. Particular attention is paid to screening the photometer disc from stray light. A series of screens E are supported by a lazy-tongs arrangement attached to the photometer box and moving with it, whereby the screens are kept equally spaced and the entrance of stray light is effectually prevented. All parts of

the apparatus are painted dull black. The scale of the photometer is direct reading in candle-power, the 16-candle-power point at the center of the scale.

For central station, or for lamp-factory use, a number of the refinements which have been introduced into the above photometer may be omitted and the apparatus may in this way be considerably simplified. The operation of the photometer is as follows:

First, several standardized incandescent lamps are used. One of these lamps is placed in the rotator at L and brought to its standard voltage. Supposing this to be a 16-candle-power lamp, the sight box is set to read 16 candle-power. Then, by adjusting the rheostat R″, the lamp L′ is brought to the point where its light just balances the light from the standard 16-candle-power lamp and the voltage on L′ is noted. By a repetition of this operation and by checking with other standard lamps, it is possible to adjust L′ with great accuracy, so that the photometer is direct reading. The noted voltage on L′ is then maintained during half a day, provided there is no change of photometer operators during this time. On account of the individual peculiarities of different operators the voltage required on L′ to make the photometer direct reading varies from operator to operator. Hence, the operation of setting the working standard must be repeated whenever operators are changed. The substitution method used eliminates errors from the results obtained on the test lamps due to individual peculiarities and to lack of symmetry of the apparatus.

Ammeter Corrections. The voltmeter terminals may be so placed that the ammeter in the circuit will or will not record the current which passes through the voltmeter. In case this current is recorded, ammeter readings must be corrected for it. The ammeter can best be calibrated from time to time by the use of a standard ampere lamp, a lamp, the current consumption of which has been carefully determined at a given voltage or series of voltages. By using such a lamp the necessity for making a separate correction to the ammeter for voltmeter current may be avoided, the latter appearing merely as a part of the error of the instrument.

Wiring of the Photometer. There are two plans for wiring the bar for the photometry of incandescent lamps. For accurate work, where a storage battery furnishes a steady voltage, the system of separate circuits should be employed. This is shown in Fig. 22. An adjustable resistance is placed in series with each lamp and the

potential is adjusted separately and independently to the required value. A voltmeter connected through a throw-over switch serves to measure the potential on either lamp. It is even better to supply the two lamps from separate batteries.

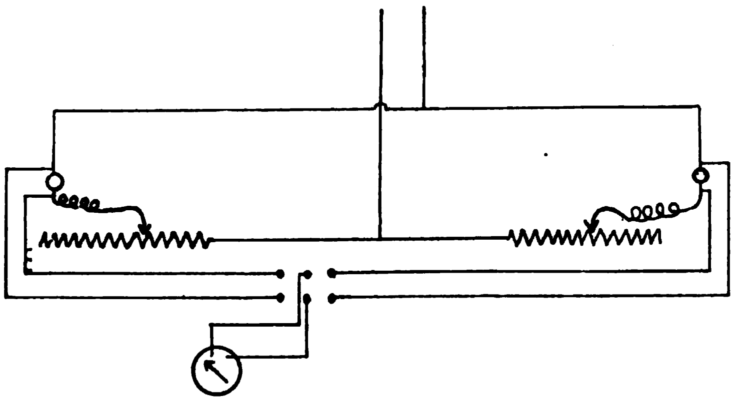

FIG. 22.—Diagram of Separate Circuit Wiring.

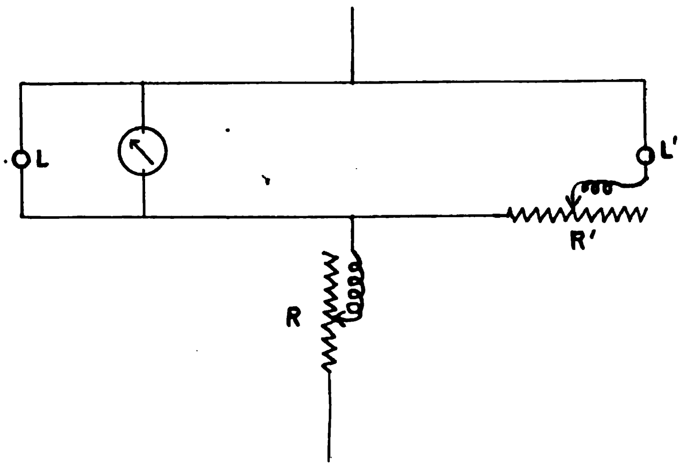

FIG. 23.—Diagram of Similar Circuit Wiring.

When the voltage is not steady, the system of "same-circuit" or "similar-circuit" wiring should be adopted. In it the lamps are placed in multiple with each other, and in series with a rheostat R as shown in Fig. 23. A slider rheostat R′ is placed in series with the working standard lamp L′. This should be wound with

wire of low-temperature coefficient. The operation is as follows: A reference standard lamp is placed at L and is brought approximately to its proper voltage by manipulating R. The working standard is then brought to its right candle-power by adjusting R′ until the photometer disc shows a balance. A reference standard of different voltage is placed at L and without disturbing R, R′ is changed until the photometer is again balanced. This gives two positions of the slider R corresponding to lamps of two different voltages at L. The slider may from these two positions be graduated so that the proper voltage can be impressed on L′ for a lamp of any voltage at L simply by moving the slider to the proper position as indicated by this graduation. After this adjustment has been made, the lamp to be measured is placed at L and L′ is brought to the proper voltage by a movement of the slider to the mark corresponding to the voltage at which L is to be measured. If the voltage on the line varies, the voltage on both lamps suffers proportional variations, and the accuracy of the measurements is not seriously impaired. In this way lamp tests can be made without the use of a voltmeter. The wiring can easily be so arranged that it can be changed from separate circuit to same circuit by throwing a switch or two.

The "Sliding-Scale" Photometer. This form of photometer is much used in factory practice in rating incandescent lamps for voltage. It is wired according to the same circuit plan, and the voltmeter is dispensed with entirely. The scale of the photometer is graduated to indicate voltages instead of candle-powers. The principle is as follows:

Suppose that a lot of 16-candle-power lamps of voltages ranging from 112 to 120 are under test. The working standard lamp on the photometer is set by putting a 116-volt, 16-candle-power standard lamp in the test end of the photometer and adjusting the rheostats until the photometer setting comes in the middle of the bar. The voltage on the standard lamp during this operation need not be exactly 116, but should not vary too widely therefrom. When this adjustment has been made, any other similar 116-volt lamp will give a setting in the middle of the bar, but a lamp intended for a lower voltage will give what is, from the candle-power point of view, a higher setting and vice versa. If, now, the relation between the voltage variation and candle-power variation of such a lamp is known, the bar may be divided so as to indicate voltages

instead of candle-powers. Or, the bar may be graduated empirically by photometering a series of lamps already rated for voltage by regular photometric methods. This style of photometer is adapted to the very rapid rating of lamps to a degree of accuracy sufficiently great for commercial purposes. It labors under one great defect, which arises from the fact that lamp filaments with different degrees of treatment do not have the same voltage-candle-power relation. In consequence of this it is necessary either to have different scales for different types of filament, or to use a given scale only within narrow limits of voltage.

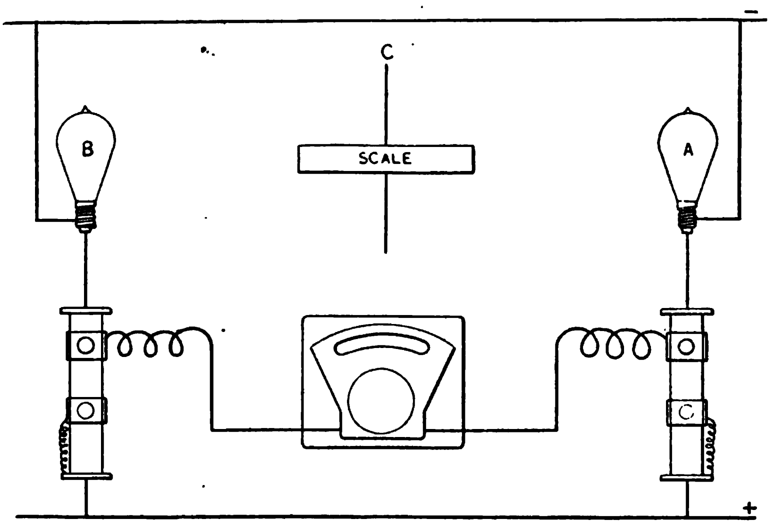

FIG. 24.—Plan of Differential Wiring.

Differential Wiring. Another system of wiring which is particularly applicable to photometers employed in inspecting lamps for accuracy of voltage rating is the "differential" system illustrated in Fig. 24. In this system a low-reading voltmeter is used to indicate the difference between the voltage on the working standard lamp and the test lamp. In the preliminary setting of the photometer the rheostats are so adjusted that the photometer setting comes at the mid-point of the bar when a standard lamp is in the test-lamp end of the photometer, and the voltmeter indicates the difference between the true-rated voltage of the standard lamp and the basic voltage chosen for the photometer. The latter

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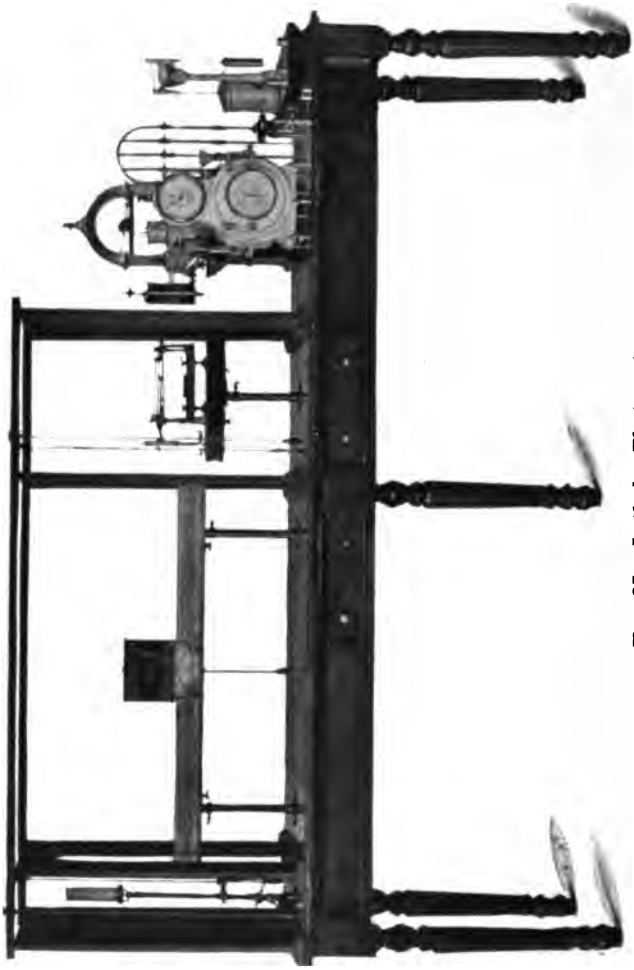


FIG. 25.—Letheby Photometer.

may be made 100 volts when testing lamps of the 100 to 120-volt type. In this case the true voltage of a test lamp is the voltage indicated by the voltmeter plus 100 volts. If the pressure in the supply circuit is variable it leads to more reliable results to use a voltmeter having its zero in the center of its scale, and to add or subtract its indications, taking the basic voltage at some mean value, as 110 volts.*

Photometers for Gas Testing. A well-known form of photometer for determining the illuminating power of gas is the Letheby (Fig. 25). This is a simple bar photometer, using a Bunsen or Leeson disc. The bar is a vertical board of seasoned wood, attached to a rail which forms the base of the board. The photometer carriage straddles the board and runs on wheels which rest on the rail. The scale is marked on the board and is graduated so as to be direct reading in terms of the standard habitually employed. The preferred distance between lights, according to the American Gas Institute, is 60 inches. The proper location of the lamps is indicated by plumb-bobs, while the rest of the table is equipped with the necessary gas-measuring and controlling apparatus, such as precision meter, pressure governor and pressure gauge.

In England, the London Gas Referees have preferred the Harcourt table photometer, which in principle is a modified Foucault photometer, and in which the photometric setting is made by varying the flow of gas which is being tested until a balance is established.

LECTURE II

Portable and Illumination Photometers

Weber Photometer.† This may be taken as the prototype of most of the illumination photometers for precision work which are in use at the present time. A view of the instrument, as a whole, is shown in Fig. 26, and the same is shown again in cross-section in Fig. 27. The tubes A and B are affixed to each other in such a way that B can rotate about the axis of A and can be fixed at any required angle with the vertical. In the lantern d is a small benzine lamp. This is equipped with a flame measure at q so

* See Marshall's article in the Transactions of the American Institute of Electrical Engineers, Vol. XX, p. 77.

† See Weber, Journal für Gasbeleuchtung, 1898.

that the height of the flame can be adjusted to just 20 millimeters by turning the knob T. Within the tube A is a milk-glass plate f, which can be moved back and forth along the axis of the tube by means of the rack and pinion v, and the distance of which from the flame can be read on the millimeter scale r. The illumination of the plate f is inversely proportional to this distance r. At the

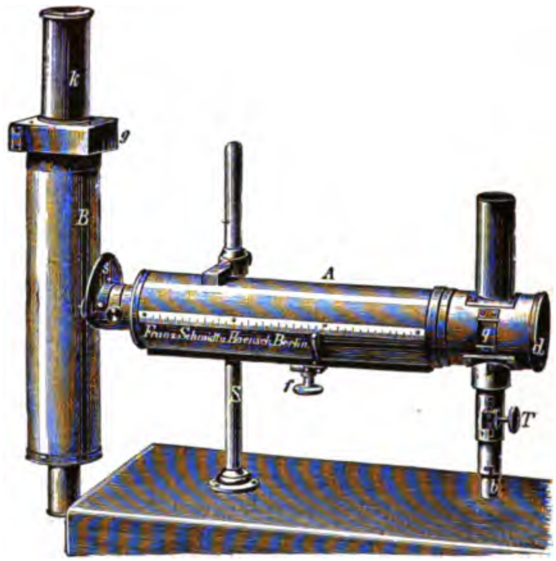
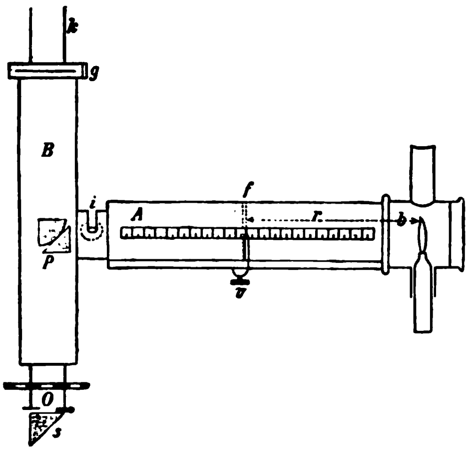


FIG. 26.--Weber Photometer, View.

intersection of the axis of the tubes A and B, is placed a Lummer-Brodhun prism p, whereby the observer in looking in at O sees the illuminated plate f, and whatever else is in the prolongation of the tube B. If, for instance, the tube B is pointed toward the illuminated surface of a white card, this white surface is seen contiguous to the surface of the screen f, and by moving the screen f the brightness of f and the brightness of the card can be made equal. From the reading r, using a previous calibration of the instrument, the illumination of the card can be determined. If the distance between the lamp and the card which it illuminates is known, the candle-power of the lamp can be computed by dividing the illumination by the square of the distance. The instrument, however, is equipped with other means for measuring candle-power. The box g near the end of the tube B is arranged to

receive one or more of a series of milk-glass plates furnished with the instrument. If the tube B is pointed toward the lamp, and the illumination on the plate in g is measured by f, the candle-power of the lamp can be determined. Here, again, a previous calibration of the instrument is required.

There is also furnished with the instrument a strongly diffusing plate, which can be fitted to the end of B in place of the tube k. This plate can be used instead of the card for measuring general illumination. When this plate is used, the instrument requires still another constant of calibration.



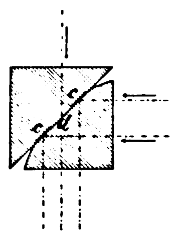


Fig. 3.

FIG. 27.—Weber Photometer, Section.

The Weber photometer has done excellent service for many years. Its chief disadvantage is the benzine flame which, however, can readily be replaced by a miniature tungsten lamp held at constant current. With the benzine flame, a variation of 1 millimeter in height corresponds to an error of approximately 5 per cent, so that this adjustment, which is not an easy one to make in any case, must be carried out with great precision. Trouble is sometimes experienced with this photometer, due to light leaking about the screen f or to diffuse reflection from the interior of the tube A.

Furthermore, when the milk-glass plate is near the clear glass which protects the benzine flame, multiple reflections between these plates may cause a departure from the inverse square law. These difficulties may be overcome by calibrating the scale. While

more convenient instruments have been produced in recent years, it cannot be said that any is applicable to a greater diversity of uses than the Weber.

Sharp-Millar Photometer.* This instrument is designed particularly with a view to a wide range of usefulness, to convenience

FIG. 28.—Sharp-Millar Photometer.

in handling and accuracy in results. A view of it is shown in Fig. 28, and a plan and elevation in Fig. 29. The body of the photometer is a hard-wood box about 2 feet (61 cm.) in length, having a hinged cover so that the entire interior is accessible. The movable part is the working standard which is a miniature tungsten

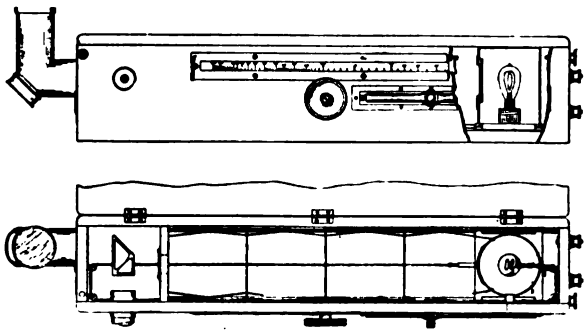


FIG. 29.—Side Elevation and Plan of Photometer. Sharp-Millar Photometer.

lamp. The working standard carriage is moved by means of an external knob which acts on a cord and pulleys. The light from the lamp shines on a translucent glass plate near the left-hand end of the photometer box proper. The photometric device is a modified Lum-

* See Electrical World, January 25, 1908.

mer-Brodhun prism in which, by the addition of another totally reflecting surface, rays from opposite directions are brought to the sight tube. At the extreme left end of the photometer is fixed an elbow tube through which the light passes to the photometer prism. This tube may be turned to any angle, and hence serves for the reception of light or illumination from any direction. In the elbow of the tube is a reversible plate, one side being a diffusely reflecting surface used in measurements of candle-power, and the other side a mirror used in connection with a diffusing translucent plate of glass at the end of the tube used as a test plate in measuring illumination.

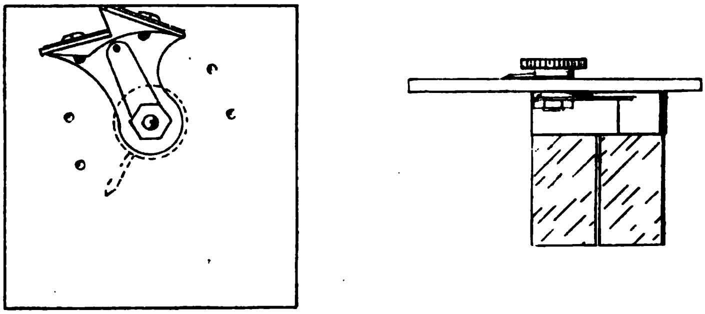


FIG. 30.—Diagram of Screen System. Sharp-Millar Photometer. Absorbing Screens.

This test plate is removable. The scale of the photometer, which is direct reading in candle-power or foot-candles,* is on translucent material, and is so arranged that by turning a knob which raises a shutter on the inside of the box, the light from the comparison lamp shows the position of the pointer on the scale, a feature which is of much practical convenience. A system of movable screens is arranged inside the box, whereby no light reflected from the sides of the box is able to reach the diffusing glass window. In order to extend the range of the instrument, two absorbing screens are provided, as shown in Fig. 30. One of these has a higher absorbing coefficient than the other. They are arranged in such a way that by turning a knurled head either screen may be brought into the path of the light either from the working standard or from the unknown source. One of the screens transmitting,

* Since 1 foot-candle equals 10.76 meter-candles or lux it is evident that the working standard lamp can be adjusted so that the scale reads directly in lux with a constant of 10.

roughly, 10 per cent of the light, and the other 1 per cent of the light, the range of the instrument is from 0.01 part of the minimum reading of the scale to 100 times the maximum scale reading. The instrument is used as follows:

1. For measuring candle-power, the elbow tube is turned toward the lamp to be measured, and the diffusing side of the elbow plate is turned inward. The distance between the lamp and the elbow plate is adjusted equal to that given in the calibration certificate of the instrument for making the instrument direct reading. Or, the instrument may be recalibrated by reference directly to a standard of light. Readings of candle-power are then taken from the scale.

2. Measurement of illumination. *First Method.* The mirror side of the elbow tube is turned in and the diffusing test plate is placed on the end of the elbow tube. This test plate is then brought into the plane in which the illumination is to be measured and settings are made as before. With the proper current through the working standard lamp, the results are given directly in foot-candles of illumination. *Second Method.* A detached test plate is used. This should be a flat plate with a very perfectly diffusing surface. This test plate is placed in the plane in which the illumination measurements are to be made, the diffusing plate is removed from the end of the elbow tube, the mirror being left turned in. The photometer is then placed in a convenient position with the elbow tube turned toward the test plate. The position should be so chosen that neither the instrument nor the observer throws a shadow or disturbs the illumination conditions on the test plate. In looking into the eye-piece, the illuminated test plate is then seen directly in the field, and its brightness may be balanced against the brightness of the diffusing glass plate in the photometer. The calibration of the instrument for use after this plan will not be the same as with the detachable test plate on the elbow tube, since the reflection coefficient of the detached test plate and the transmission coefficient of the elbow-tube test plate will not be the same. The distance between the detached test plate and the photometer is immaterial, provided the test plate is so large that the field of the photometer is entirely covered. The angle at which the test plate is viewed should not differ too much from normal, since, if it does, the variations of the reflection of the test plate from the cosine law become so

marked as to introduce too great an error. Within proper limits, the magnitude of the angle makes no difference in the results.

The photometer may also be used for the measurement of specific intensity, etc., provided it is first calibrated for this purpose.

The photometer is used solely by the substitution method. It is calibrated by reference to known standards of candle-power or to known illuminations, the current through the working standard lamp being adjusted to such a value that the instrument is direct reading in the required unit.

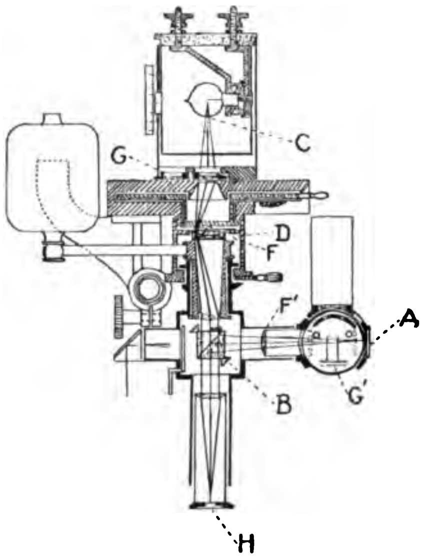


FIG. 31.—Beckstein Photometer.

Beckstein Photometer. This photometer is shown in Fig. 31. It makes use of the Lummer-Brodhun prism and of a miniature incandescent lamp as a standard. The photometric settings are made, however, by a variable sector disc on the plan of the Brodhun sector. An illumination test plate is shown at A. The tube carying A can be rotated to any required angle about the instrument. Candle-power measurements can also be made with the instrument by rotating the shell to which A is affixed into the position where the shielding tube shown in the illustration comes in line with the aperture in G′. A motor is required to drive the Brodhun sector arrangement.

Blondel and Broca Photometer. The photometric scheme consists of two crossed prisms B (Fig. 32), in the face of which are the diffusing plates G and G′. This portion of the apparatus can be used as an ordinary photometer on a bar. To it can be attached tubes which have lenses F and F′ at their extremity, and which are fitted with the cat's-eye photometric diaphragms D and D′. At the end D may be attached a lantern containing a flame standard light. At the end D′ may be attached the rotating elbow tube carrying the mirror E′ and a test plate A. Evidently the use of this photometer is similar to that of others described.

Marten's Universal Photometer.* This photometer employs the same bi-prism arrangement to produce the photometric fields that

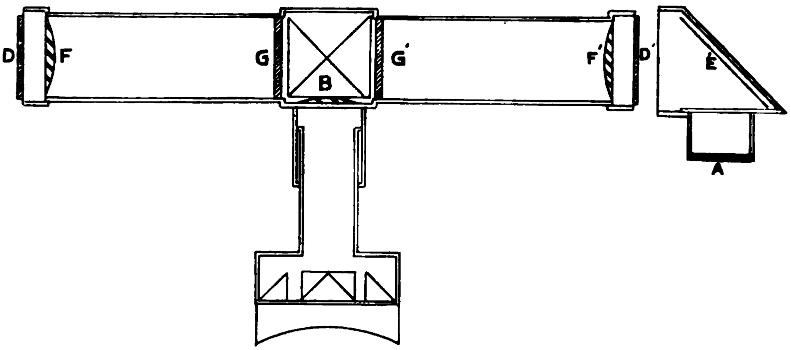


Fig. 32.—Blondel-Broca Photometer.

have been described in the Marten's photometer above. The present instrument, which is shown in Fig. 33, has a miniature incandescent lamp as standard, and employs the polarizing principle for photometric setting. The rays of light from the standard lamp and from the unknown source which reach the photometer by way of the tube T pass through the Wollaston prism P, by which each beam is divided into two beams polarized in planes at right angles to each other. The ordinary beam from one source and the extraordinary beam from the other are deflected out of the field. After passing the bi-prism the beams traverse the Nicol prism N. If the plane of the Nicol lies at 45° to the planes of polarization of the beams which have passed the Wollaston prism, both rays are reduced in intensity by an equal amount. In turning the Nicol from this position, one beam is diminished in brightness

* Verh. der Deutschen Physikalischen Gesellschaft. 1903

and the other increased. The position of the Nicol is read from a divided scale. The opaque diffusing plate F, which is used for candle-power measurement, may be replaced by a milk-glass plate for illumination measurements or may be removed entirely for the measurement of surface brightness. The range of the instrument is increased by the use of smoked-glass screens which are placed before the opening b.

Auxiliary Apparatus

Certain apparatus is necessary for determining the photometric elements of sources of light. Not only is the candle-power in a given direction wanted, but often candle-power in various directions in a horizontal plane, or the mean horizontal candle-power is required. It is also requisite to know candle-power in various directions in the vertical plane passing through a lamp, and finally the mean spherical candle-power and the mean hemispherical candle-power need to be known. In order to measure these photometric elements, various mechanical devices are required.

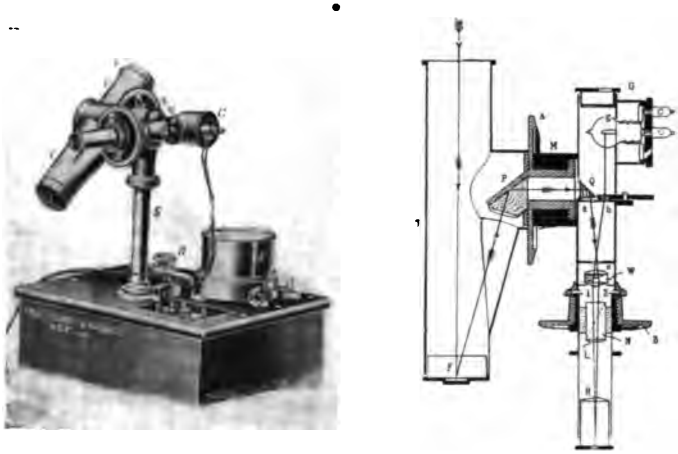


FIG. 33.—Marten's Universal Photometer.

Mean Horizontal Candle-Power

The mean horizontal candle-power of a source of light may be measured by taking its candle-power at a sufficiently large number of positions equally spaced about the lamp in a horizontal plane. For instance, in most cases, by taking 36 measurements 10° apart.

and averaging these, the mean horizontal candle-power is obtained. In the case of incandescent lamps a simpler method is applicable, which is in practically universal use in this country. This consists in rotating the lamp at such a speed that the impression on the eye viewing the photometer disc is one of constant, or nearly constant, illumination. For carbon-filament lamps this speed is taken at about 180 revolutions per minute. With lamps having a larger

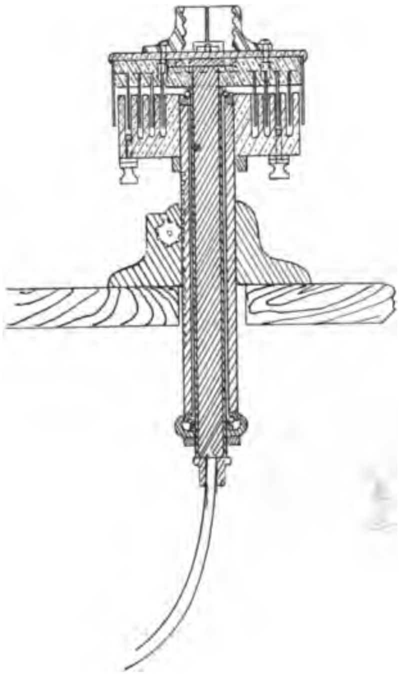


FIG. 34.—4-Cup Rotator.

number of parallel vertical portions of the filament, such as tantalum and tungsten lamps, a lower speed of rotation is sufficient. In any case the speed of rotation should be high enough so that no very strong flickering is observed, and at the same time it should not be so high as to produce any marked deformation of the filament. The rotators for incandescent lamps are made in large variety of forms, the principal requirement being that the apparatus should be sufficiently strong and rigid, and that the arrangements for carrying current to the rotating portions should be per-

fectly reliable. For continuous work, it is most common to use mercury contacts for this purpose. Where brushes are used, it is necessary that the potential on the lamp should be taken from the collector rings by an extra pair of brushes, insulated from the pair which bring current to the rings. Thereby any drop in voltage taking place at the brush contacts is not measured as part of the voltage on the lamp. As an extra precaution, in precise work, voltage may be taken from the shell of the lamp itself. For this purpose the socket of the lamp is split and current is led in at one

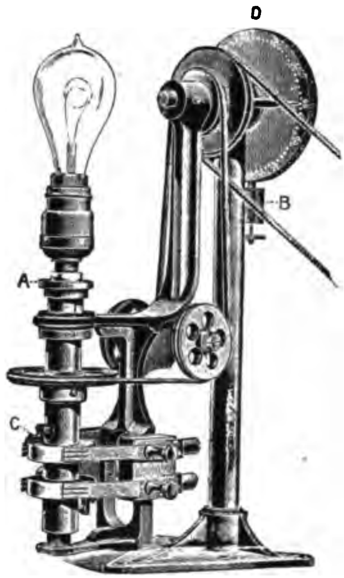


FIG. 35.—Compound Rotator.

side and voltage taken out from the other side. A rotator combining a socket of this description, with four mercury cups, is shown in section in Fig. 34. Evidently a similar arrangement can be made for lamps which, like tungsten lamps, are best burned in a pendant position.

The method of the German Elektrotechnischer Verein for getting the mean horizontal candle-power of incandescent lamps consists in placing behind the lamp two mirrors, one at each side, so that the mirrors reflect the light of the lamp on to the photometer disc. These mirrors make with each other an angle of 120°. The line of the intersection of these two mirrors lies 9 centimeters

behind the axis of the lamp. The photometer disc is then illuminated by the light of the lamp directly and by the light from two other directions equally spaced in the horizontal plane received by reflection. This method has been used at the Electrical Testing Laboratories in the photometry of tungsten lamps.

In Fig. 35 is shown a compound rotator; that is, one in which the lamp can be measured in all vertical angles about the lamp, and

FIG. 36.—6-Mirror Rotator.

the values so obtained can be used in computing the mean spherical candle-power.

By means of the device * shown in Fig. 36, the mean candle-power in two directions is obtained in each measurement. The frame about the lamp carries six mirrors, so that if the frame is set at 10° from the vertical, the photometer receives light simul-

* Physical Review, Vol. II, p. 181, 1900.

taneously from 10° from the zenith and 10° from the nadir of the lamp. The use of this arrangement decreases the number of measurements required when mean spherical candle-power is to be obtained. If measurements are made by the substitution method, the absorption of the mirrors is eliminated.

A greatly enlarged apparatus on this plan, using, however, only three mirrors is in use in the Electrical Testing Laboratories for the measurement of the distribution about shades and reflectors, and is illustrated in Fig. 37. These mirrors have a dimension of 22 by 30 inches (55 by 75 cm.).

A design of three-mirror distribution apparatus, as modified by Mr. W. F. Little, is shown in Fig. 38.

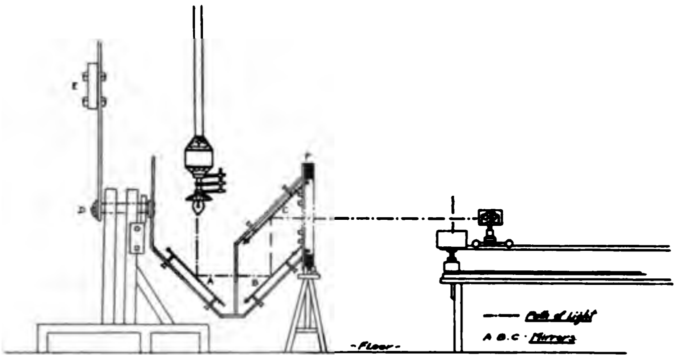


FIG. 37.

The distribution about lamps may also be obtained, using some scheme involving the elevation of the lamp above the plane of the photometer, as in Fig. 39. If the lamp is elevated to such a height above the photometer that at the photometer head its rays intersect the photometric axis at an angle θ, then the rays so intersecting the photometric axis proceed from the lamp at an angle below the horizon equal to θ. If, now, the photometer is rotated through an angle $\frac{1}{2}\,\theta$, the rays from the lamp being measured, and from the standard lamp, will fall upon the photometer disc at equal angles, and photometric measurements can be made by moving the standard lamp. Wedding has used this arrangement in the photometry of arc lamps, extending it by placing a photometer bar and photometer on each side of the lamp and making simultaneous measurements in two directions. Dibdin's radial photome-

ter is constructed on this principle. In this photometer the distance between the lamp and the photometer disc is kept constant by means of an arm, and by a suitable arrangement the photometer disc is tilted so as to bisect the angle between the rays coming from the lamp and the rays from the working standard. In using a photometer of this character, particular care must be taken in screening the disc from stray light.

FIG. 38.—Three-Mirror Light Distribution Apparatus.

An arrangement which has been frequently used in the photometry of arc lamps is the crane illustrated in Fig. 40. This is used in connection with a mirror M placed at 45° to its axis, the axis of the mirror being located in the photometric axis. By means of this simple arrangement, which is due to Ayrton and Perry, the light from the arc lamp can be measured in any vertical angle except the zenith. In an arrangement used in the photometry of arc lamps in the engineering laboratory of the Massachusetts Institute of Technology, the photometer is placed on a long steel

structure which is movable about a horizontal axis. At the opposite end of this structure the arc lamp is suspended. When this structure is tilted through an angle θ, the rays of the lamp proceeding at $-\theta$ are photometered. The arrangement is very cumbersome and expensive.

A very simple arrangement for measuring the intensity of light at various vertical angles, and which is described here for the first time, is illustrated in Fig. 41. The long arm shown in this figure, which can be set at any vertical angle about the lamp,

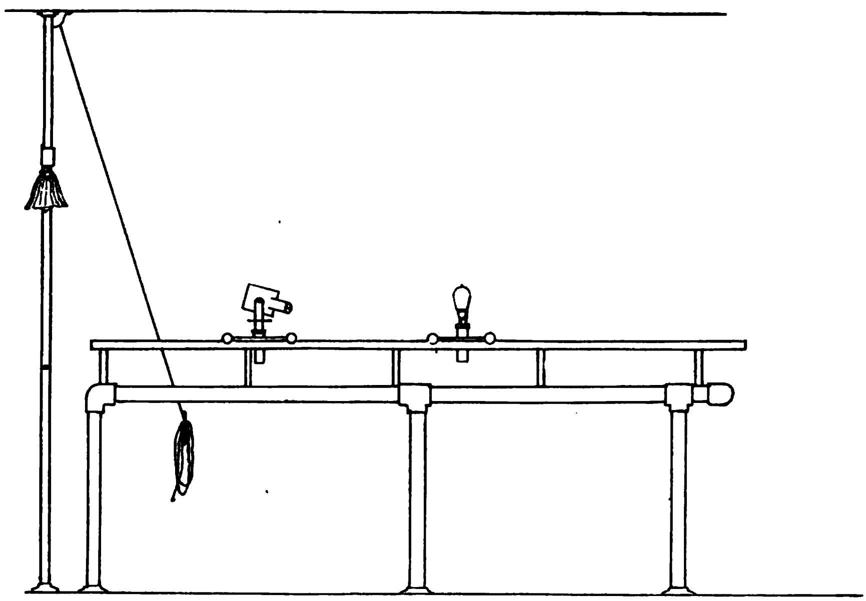


FIG. 39.—Elevated Lamp.

carries at its extremity simply a diffusing white surface S. The apparatus is especially intended to be used with the Sharp-Millar photometer, but may be used with any other suitable photometer with Lummer-Brodhun cube. The small mirror M at the end of the rotating shaft enables the observer in looking into the eyepiece, to see the illuminated disc at the end of the arm. He then compares the brightness of this disc with the brightness of the other side of his photometric arrangement. The distance to the lamp being fixed, the brightness of the disc is directly proportional to the candle-power of the lamp at the angle at which the

arm is set. It will be seen that the idea of this arrangement consists in substituting for an arrangement whereby the lamp is moved about the photometer, or the photometer and track moved about the lamp, an arrangement whereby one side of the photometer disc is moved about the lamp, all of the rest of the apparatus being stationary. It will be seen that the size of the source of light which can be measured with this arrangement is not limited by the size of any mirrors.

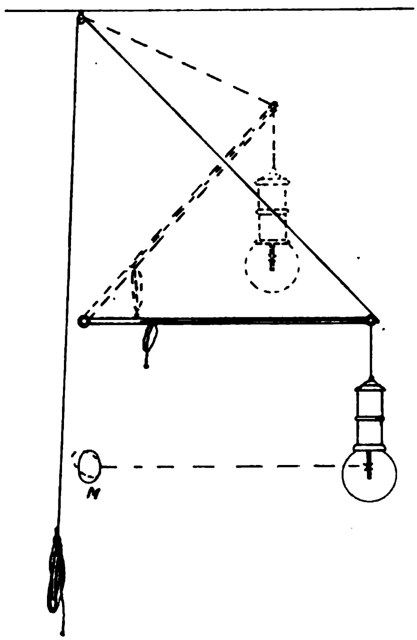


FIG. 40.—Arc Lamp Crane.

One of the difficulties in the photometry of arc lamps is the unsteadiness of the light due to the movement of the crater. It was to overcome this difficulty that Wedding employed two photometers. Matthews * has employed for this purpose two mirrors, as shown in Fig. 42. These mirrors are on arms which move about an axis passing through the axis of the apparatus. They are set at corresponding angles on each side of the arc lamp. The illumination then on the photometer disc is proportional to the

* Report to Committee on National Electric Light Association, 1900. Physical Review, Vol. 7, p. 239, 1898.

sum of the intensities of the arc lamp at two angles on opposite sides of the lamp. The rays strike the photometer disc at a considerable angle of incidence, but this difficulty and the difficulty

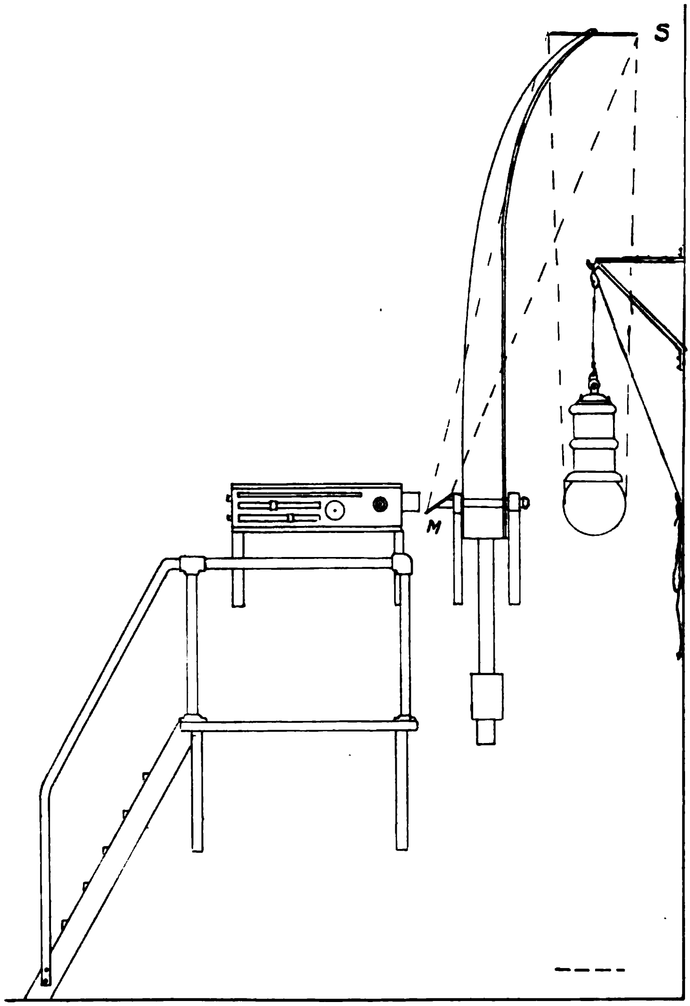


FIG. 41.—Long Arm.

due to the absorption of the mirrors is eliminated by the use of the substitution method. This is one of the most convenient arrangements known for the photometry of arc lamps. In these tests a device was employed to obviate the difficulty due to the

difference in color between the arc light and the light of the incandescent lamp standard, which has seldom been used in photometry. The plan was to use a rotating sector disc with very narrow openings so as to cut down the illumination on both sides of the photometer disc to so low a value that color vision practically ceases. The results so obtained are probably not comparable with those obtained by ordinary methods. The records of the photometer settings were made using a recording device consisting of a drum placed axially along the photometer track, and a punch on the photometer carriage. The punch was operated by an electromagnet and made a hole in a sheet of paper on the drum as a record of the photometric setting.

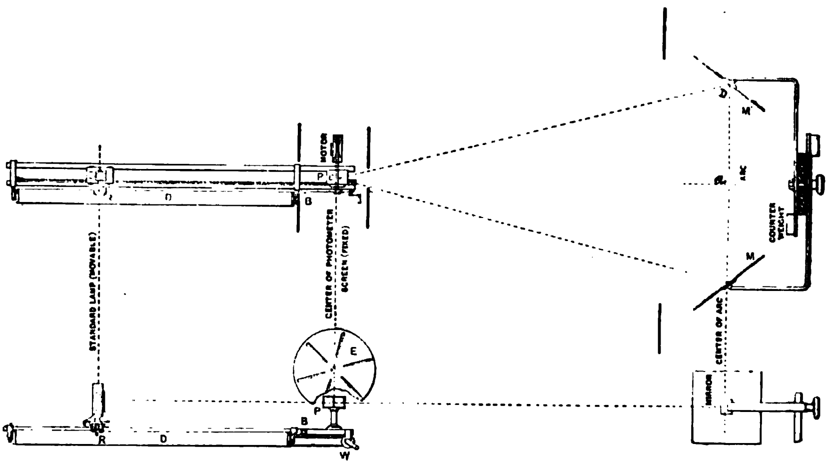


FIG. 42.—Matthews Arc Photometer.

Integration Apparatus

Certain apparatus has been devised in recent years for the purpose of giving in one reading the mean spherical or mean hemispherical candle-power of a source of light, or the corresponding quantities, spherical or hemispherical, of luminous flux. This apparatus is divided into two general classes; namely, summation and integration apparatus. The summation apparatus depends upon the same operation as is employed in determining any of these quantities by a series of measurements made at different vertical angles. The theory shows that the mean spherical candle-power of a source of light can be obtained by multiplying by a

constant factor a series of terms made up of the intensity of the source in various vertical angles, each multiplied by the sine of the angle if the angles are reckoned from the vertical line, or by the cosine if the angles are reckoned from the horizontal line. In the summation apparatus individual mirrors are placed at various angles and so arranged that the summation of the intensities which they throw upon the photometer disc is proportional to the mean spherical intensity. In integration apparatus, on the other hand, all angles are used, and the process is a true integration. In practice, all apparatus, whether summation or integration, is commonly designated as "integrating apparatus."

Two principal types * of summation apparatus are the Matthews type and the Russell-Léonard type. In the first, the mirrors are equally spaced and the intensity of each beam of light is reduced in proportion to the cosine of the angle of its emission with the horizontal. In the second type, the mirrors are so spaced that they all cover zones of equal areas of the sphere surrounding the lamp.

Matthews Integrating Photometer for Arc Lamps

Matthews' original arrangement consisted of a vertical ring of 24 large trapezoidal mirrors, in the center of which the lamp was placed. The mirrors were so set with respect to each other that they formed a truncated pyramid of 24 sides. Viewed from the photometer disc, an image of the arc was seen in the center of each mirror, so that the disc was illuminated by rays proceeding from the arc at all angles of inclination with the vertical.

The diminution of the intensity of the beam from each mirror, proportional to the cosine of the angle of inclination which it made with the horizontal, was accomplished by interposing between the mirror and the disc a sheet of glass on which a uniform layer of smoke of the required thickness, as shown by experiment, had been deposited. Inequalities in the reflecting power of the mirrors were eliminated, since the absorption of the smoked glasses and of the mirrors was taken together, and each smoked glass was adjusted to its particular mirror.

* Trans. Amer. Inst. of Elec. Eng., 19, p. 677, 1901; 20, p. 1465, 1902. L'Eclairage Électrique, 40, p. 128, 1904. Jour. Inst. of Elec. Eng., 32, p. 631, 1903. Bulletin, Bureau of Standards, I, 1905, paper by Hyde.

In the Matthews photometer in the Electrical Testing Laboratories the pyramid of mirrors, each of which has the dimensions of $12 \times 14 \times 16\frac{1}{2}$ inches, occupies one end of a room 70 feet long. (See Fig. 43.) A hardwood track is laid on the floor of this room, extending nearly from end to end. Arranged to roll on this track are a stand carrying the frame containing the smoked glass sectors and a table on which is placed the photometer bar. The mirrors are hinged so that their inclination to the backboard can be varied. By this means they can be adjusted to focus on the photometer disc at

FIG. 43.—Arc Photometer Mirrors, Matthews.

whatever distance the latter may be. For measuring very powerful lights, the photometer table and the smoked-glass sectors may be moved to the far end of the room and the mirrors are tilted to correspond, and vice versa.

The photometer sight box is mounted rigidly in a good-sized box, which shields it and the eyes of the operator from stray light. The track employed is of the Reichsanstalt pattern. The distance of the comparison light from the disc is measured by means of a steel tape attached to the lamp carriage and passing around pulleys at the ends of the track. The photometric settings may also be recorded by the device, which also is due to Matthews, and which is referred to above, consisting in a roller extending longitudinally along the bar, on which a sheet of paper is wrapped. Attached to the lamp carriage is an electro-magnet which carries a punch

which perforates the paper when the circuit is closed. A key controlling this circuit is manipulated by the photometer operator. By use of this a large number of settings may be recorded with great rapidity, a matter of great importance in dealing with a rapidly fluctuating source of light, such as an arc lamp. After completing a set of measurements the readings are averaged by estimation, and are interpreted by use of a scale on the photometer track.

Arc lamps under test are suspended on little trolleys running on an overhead track. This track is in the form of a loop outside the photometer room, but having a switch spur extending inside the room through the backboard of the pyramid of mirrors. By means of this arrangement the lamps may be successively introduced into the photometer without interrupting their burning or disturbing their normal régime.

Measurements of the vertical distribution of candle-power are made with the same arrangement, only the smoked sectors are raised out of the way, and all the mirrors excepting the two corresponding to the required vertical angle are closed by blackened covers. These measurements have subsequently to be corrected for the difference in the reflecting powers of the mirrors, taking that of the horizontal pair as unity.

In practice with this photometer, both in the determination of mean spherical candle-power and of vertical distribution, the arrangement is first standardized by making settings against a standardized incandescent lamp of high candle-power. This lamp is placed with its axis horizontal in the center of the mirror system. By working in this way it becomes unnecessary to determine the distance between the lamp and the photometer disc, as well as the absolute value of the coefficient of absorption of the mirrors, etc.

Matthews Integrating Photometer for Incandescent Lamps *

A view of this photometer is given in Fig. 44. The lamp to be measured (which is not visible in the figure) and the photometer box are placed on opposite sides of the vertical support and in the axis of a narrow half-ring. This half-ring carries 11 pairs of mirrors with each mirror inclined at an angle of 45° to the ring and 90° to its mate. By this arrangement, light emitted by

* Transactions of the American Institute of Electrical Engineers, 1901. National Electric Light Association, 1901.

the lamp at 11 different angles in the vertical plane is caught by the mirrors and is reflected back along paths parallel to their paths of emission to the photometer disc. To diminish these beams proportionally to the cosine of the angle with the horizontal, advantage is taken of Lambert's cosine law which declares that the illumination produced on a diffusely reflecting surface is propor-

FIG. 44.—Matthews Integrating Photometer.

tional to the cosine of the angle of incidence of the rays on that surface. It follows that if in the above arrangement the photometric screen is diffusely reflecting and is placed in a vertical position, the illumination produced by a bundle of rays leaving the lamp at an angle e with the horizontal, and reflected to the photometer disc and incident on it at the same angle, will produce an illumination proportional to cos e. The total illumination on

the disc being made up of a series of such terms covering all the vertical angles will be proportional to the mean spherical candle-power of the source of light.

In the above discussion it is assumed that the source of light is one in which the effective distribution of intensity about a vertical axis is uniform. In the case of the incandescent lamp this condition is secured by rotating the lamp as in ordinary measurements of mean horizontal candle-power. In the case of sources of irregular distribution which cannot be so rotated, the mean spherical candle-power can be found by taking the mean of a series of measurements made with the lamp turned so as to present its different aspects to the mirror system.

It is assumed also that the mirrors are all exactly alike in reflecting power, and that the photometer disc is a perfect diffuser of the light falling upon it, so that Lambert's law is obeyed. Neither of these conditions is fulfilled in practice; hence it is necessary to seek some means for adjusting the apparatus to compensate for the resulting deviations. Now, the variations from Lambert's law are in the sense to make the illumination produced by oblique rays smaller than what is called for by the law, the size of the variation depending upon the amount of regular or mirror-like reflection which the disc shows. The variations from Lambert's law can therefore be compensated for by shortening the path which the oblique rays must traverse in passing from the lamp to the photometer disc. This can be accomplished by moving the corresponding mirror pairs radially inward toward the lamp and the photometer disc. The mirrors are attached to the half-ring by long-threaded pins, so that this adjustment is readily made by experiment. Variations in the reflecting power of the mirrors are compensated for in the same operation.

These adjustments hold only for the particular photometer disc with which they have been made. Matthews has determined the deviations from Lambert's law, shown by three types of surfaces. His curves for them are reproduced in Fig. 45. Evidently an adjustment effected for a Lummer-Brodhun screen would be not at all suitable for an ordinary Bunsen screen.

The position of the photometer screen is fixed and the adjustment of illuminations on it to equality may be made, either by moving the working standard along the horizontal bar of the photometer or by moving a pair of mirrors. A rod is provided to which

either the working standard or the mirror pair may be attached, and by which they may be moved.

This photometer, as constructed, may be used not only for mean spherical candle-power but for horizontal candle-power, vertical distribution, and for the direct determination at one measurement of the spherical reduction factor of incandescent lamps.

In using this photometer the mirrors must be kept clean and the surface of the photometer disc must remain protected from dirt and anything which might change its optical properties. It is

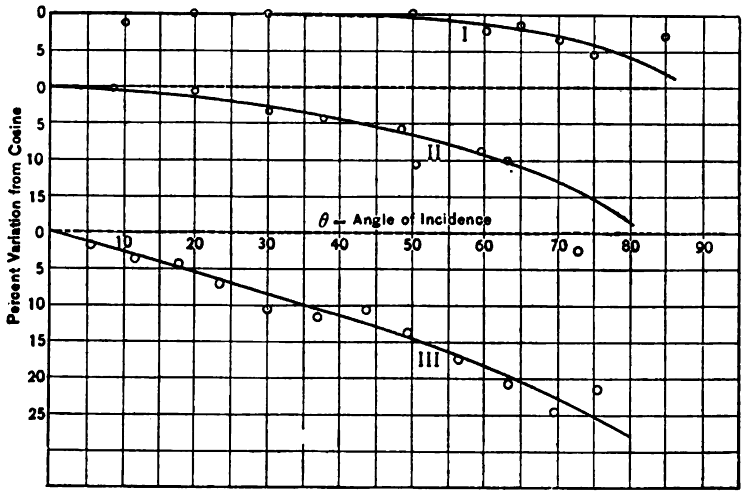


Fig. 45.—Lambert's Law and Photometer Discs.

Per cent variation from cosine relation for different screens.
I.—Lummer-Brodhun screen.
II.—Unglazed paper.
III.—Glazed paper.

important also that the optical center of the lamp under measurement shall be exactly at the center of the half-ring. Especial care should be taken to exclude stray light from the photometer disc, since on account of the numerous mirrors present stray light is liable to intrude from the most unexpected directions. The adjustments of this photometer are relatively difficult to make and to maintain.

Blondel Lumenmeter.* The source of light L (Fig. 46) is

* Bull., Société Internationale Electriciens, Vol. IV, p. 680, 1904. L'Eclairage Electrique, Vol. 3, pp. 406, 538, 583, 1895.

placed in the center of a hollow sphere of metal S, which is carefully blackened inside and out, and which is pierced with two vertical slits AA 18° in width, extending from pole to pole. Since the area of these slits is one-tenth of the surface of the sphere, one-tenth of the total flux from L will pass out through them. This flux falling on the ellipsoidal mirror MM is reflected to the diffusing screen G. The brightness of the diffusing screen is proportional to the total flux of light of the source L, and it requires only a calibration of the apparatus, which may be carried out by substituting for L a source of known luminous flux, in order to determine what the proportionality constant is.

On account of the expense of forming the ellipsoidal mirror, a cheaper but less exact form of the lumenmeter has been constructed

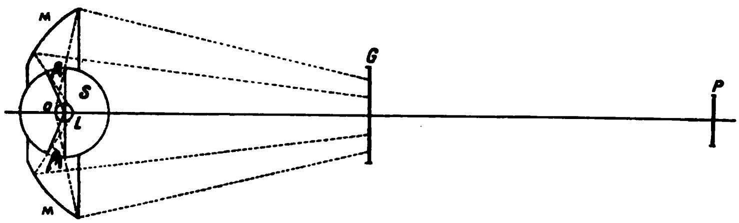


FIG. 46.—Blondel Lumenmeter.

in which a spherical surface of sheet metal covered with white paper or painted white is substituted for the mirror. This surface serves at once as diffusing screen and mirror. This apparatus cannot be used with large surfaced sources, such as arc lamps with globes.

The Integrating Sphere,* the use of which should be accredited to Ulbricht, consists of a hollow sphere, coated inside with a white, diffusing paint, and having a small window of diffusing glass set into it. The lamp to be measured is placed inside the sphere, and between it and the window is placed a white screen so that the direct rays of the lamp do not fall upon the window.

* Ulbricht. Elektrotechnische Zeitschrift, Vol. 21, p. 595, 1900; Vol. 26, p. 512, 1905; Vol. 27, p. 50, 1906. Bloch Elektrotechnische Zeitschrift, Vol. 26, pp. 1047 and 1074, 1905. Corsepius Elektrotechnische Zeitschrift, Vol. 27, p. 468, 1906. Monasch Elektrotechnische Zeitschrift, Vol. 27, pp. 669 and 695, 1906. Ulbricht & Monasch Elektrotechnische Zeitschrift, Vol. 27, p. 803, 1906. Blondel, Bull. Soc. Int. des Elec., Vol. 4, p. 687, 1904. Sharp & Millar, Trans, Illuminating Engineering Society, Vol. 3, p. 502, 1908.

Then the brightness of the glass window is proportional to the mean spherical candle-power of the lamp inside the sphere. This action depends upon the theorem that on the interior of a sphere the surface of which obeys Lambert's cosine law the illumination at any point due to light reflected from all the remaining interior surface of the sphere is the same as at any other point in the interior of the sphere. In other words, the illumination on any portion of the interior of the sphere due to the light reflected from any other portion is independent of the position of the latter, and depends upon its area and surface brightness only. For, in a sphere of radius r (Fig. 47), the illumination at a point C produced

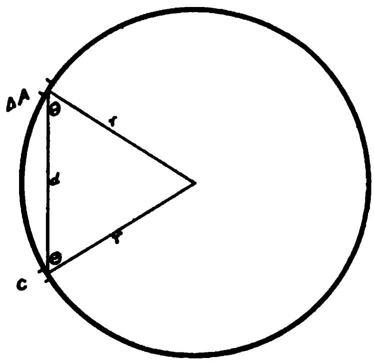


FIG. 47.—Proof of Law of Sphere.

by light reflected by another portion of the surface of the area ΔA at a distance d from the first, under the assumption that the surface obeys Lambert's law, both for emission and for incidence, is

$$E = \frac{e \Delta A \cos^2 \theta}{d^2}$$

in which e is the specific intensity of the area ΔA considered as a source of light. Substituting for d its value $2r \cos \theta$, there is obtained

$$E = \frac{e \Delta A}{4r^2}.$$

The absence of any variable distance or angle in the above equation shows that this illumination is independent of the location of the area ΔA. Hence each element of the surface of the sphere will contribute to the point C an intensity of illumination which is directly proportional to the illumination which it itself receives,

or to the flux of light which it receives. The total illumination at the point C will therefore be proportional to the total flux of light falling on the interior of the sphere; that is, to the total luminous flux of the lamp which the sphere encloses.

Integrating spheres of various diameters have been constructed from less than ½ meter up to 5 meters. The practical form of a small sphere, intended for testing incandescent lamps, is shown in Fig. 48. This sphere is equipped with two lamp sockets on hinged arms, so connected that when one lamp socket is holding a lamp inside the sphere for measurement the other lamp socket

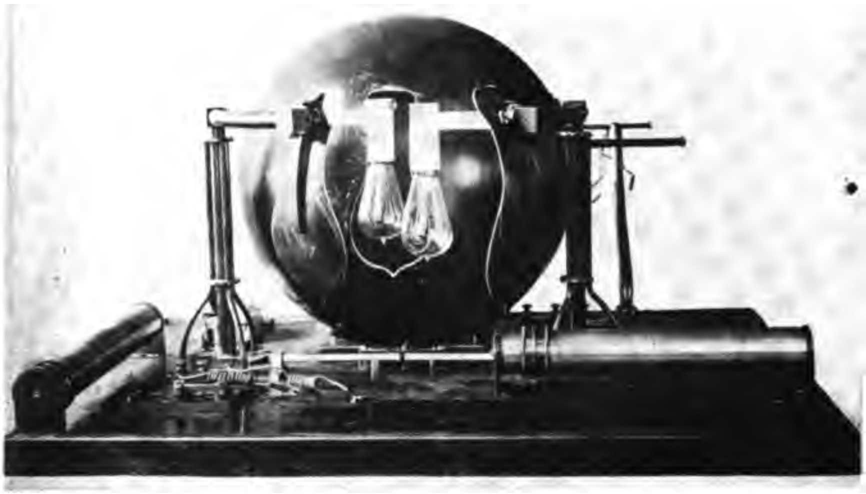


FIG. 48.—Small Sphere.

is outside the sphere, so that the lamp which has just been measured may be removed and another one to be measured substituted in its place. By the motion of a single lever, these lamp sockets are instantly interchanged. In Fig. 49 is shown another sphere of two meters diameter, intended for the photometry of arc lamps and similar large sources of light. This sphere is constructed of iron and is divided vertically into halves. Each half is on wheels running on rails, so that they may be pushed apart quite readily for access to the interior. The sphere contains not only the lamp to be measured, but also a standardized incandescent lamp by which the constant of the sphere is determined. A very important

consideration in connection with the sphere is the screen which prevents the light from the lamp under measurement from falling directly on the photometer window. This screen should be as small as it may be to accomplish the result required. Both opaque and translucent screens are used, the translucent screen being designed to transmit enough light to the window to compensate for the light which it cuts off. By the proper selection of the screen this compensation can be made very close in all practical cases.

FIG. 49.—2-Meter Sphere.

In using the sphere, the substitution method in photometry must be employed exclusively. If the sphere is correctly designed, its constant may be determined by the use of a standardized incandescent lamp, and the results of measurement will then be correct within commercial limits for other sources of light, such as arc lamps, etc. Precaution, however, should be taken to have the lamp which is to be measured in the sphere at the time when the sphere is being standardized by the incandescent lamp, for otherwise light absorbed by the lamp which is to be measured, or by its parts, such, for instance, as the housing of the mechanism of an arc lamp, or

by a diffusing globe with which it may be equipped, will not be taken account of. In measuring arc lamps it is a good precaution to cover as much of the housing as comes within the sphere with white paper.

If the lamp to be measured is lowered half way into an opening in the sphere so that its light-giving center comes in the plane of the opening, the lower hemispherical flux will evidently be delivered inside of the sphere, and the upper hemispherical flux will be delivered outside of the sphere. Under these conditions the sphere measures lower hemispherical flux or mean lower hemispherical candle-power. The principal difficulty with this procedure is to make sure that the lamp is so placed that the flux will divide itself properly.

Heterochrome Photometry

Hitherto consideration has been given to the comparison of sources of light of the same, or nearly the same, color. When the fields of a photometer are illuminated by lights of different tints the eye receives not only a quantitative difference between them, but a qualitative difference as well, and rebels against comparing two things which are not of the same kind. However, within certain limits of error, which widen as the color difference increases, it is possible to see when two fields illuminated with lights of different tints are equally bright, and so heterochrome photometry is within certain limitations possible, using the simple photometer in any one of the forms in which it has been described above.

The limitations and conditions which hedge in this kind of work should, however, be clearly borne in mind. The measurements are influenced, first, by the brightness of the photometer field; second, by the size of the photometer field, and third, by the personal equation of the observer.

Considering the effect of the brightness of the photometer field, we notice that in comparing a reddish light with a bluish one, the reddish light is relatively brighter at high illuminations and relatively dimmer at low illuminations than the bluish one. This is the Purkinje effect. The practical result of it is that in comparing an arc lamp with an incandescent lamp, for instance, the value assigned to the candle-power of the arc lamp will be higher the farther away the lamp is from the disc. As the lamp is brought nearer to the disc, and the illumination on the disc thereby in-

creased, the arc lamp apparently suffers in candle-power. Hence this candle-power, as measured by simple photometry, can be stated as a constant quantity only when coupled with it is given the illumination on the photometer disc at which the candle-power was measured. The Purkinje effect intervenes in all ordinary measurements in heterochrome photometry. It is fortunately of considerable influence on the result only when the color differences are very great or when the illuminations are very feeble. At such illuminations as are ordinarily used on photometer discs, the Purkinje effect is small. This effect is something, however, which is of importance in practical illumination. The eye being relatively much more sensitive to the blue end of the spectrum at low illuminations, those illuminants are most efficient where low illuminations are to be produced which are of bluish tint. For instance, in the lighting of streets where very feeble illuminations are of importance, an arc lamp has an advantage over an incandescent lamp which is not shown by computations of the illuminations from candle-power measurements made with a brightly illuminated photometer disc. It is therefore of importance in the practical study of an illuminant in the laboratory to know something about the value of the Purkinje effect for it, and this evaluation may be carried out by the methods of simple photometry, using both high and low illuminations on the photometer disc. From this point of view, therefore, far from being a disadvantage that the ordinary photometer shows the Purkinje effect this is a distinct advantage, since thereby the properties of an illuminant for the production of illumination of different degrees may be more definitely ascertained. If the illumination is reduced to a sufficient degree, the sense of color of the light disappears, and hence the difference in color between two illuminated fields. Under these conditions heterochrome photometry is practically homochrome photometry with very feeble illuminations. The illuminations are so feeble that the error of observation is probably much larger than would be the case if the illuminations were increased to the point where the color is plainly visible. Moreover, the result obtained under these circumstances is the result for feeble illumination only, and may differ very considerably from the result obtained with ordinary illuminations; in other words, the Purkinje effect is experienced at its maximum value. Matthews has used this method of photometry in the measurement of arc lamps, cut-

ting down the light from the arc lamp and from the comparison lamp by rotating sectors of very narrow aperture.

The second effect noted above is that when taking equally bright surfaces of red and blue, equally distant from the eye, the red appears brighter when only a very small area of each is visible. If, for instance, the field of a photometer is very small, a reddish light is given an advantage over a bluish one. This is due to the fact that the image of the field falls largely on the yellow spot of the retina which exerts a selective absorption in favor of the redder light. With fields of usual dimensions the yellow-spot effect has little influence.

The third element entering into heterochrome photometry, namely, the personal equation, is the element which influences the results most largely. As has been said, the eye rebels at comparing things with each other which are qualitatively different. There is no exact criterion for the brightness of a field of one color as compared with the brightness of a field of another color. A given observer may set up for himself a criterion with which he is satisfied, and by adhering to that criterion may make very consistent comparisons of heterochrome illuminations, but in general the criterion which he uses for the brightness of two fields will not be the same as that used by another observer. The observations of one may be quite as consistent among themselves as are those of the other. Moreover, a given observer may change his criterion from day to day, or even from hour to hour, and so may not in the long run be consistent with himself. Two observers who have been working to different criteria may, by a study of each other's photometric settings, come gradually to adopt the same criterion, after which they may continue in agreement, but the criterion adopted by both of them may not yield results which are really any nearer the truth than one of the abandoned criteria had done.

It would appear to be necessary, then, in any case where precision is required in the comparison of lights of different colors, to take the average result given by a large number of observers. Since it is impracticable to use a large number of observers in each piece of heterochromatic photometric work, it is important to bridge over the gap between the color of the standard light used in photometry and the color of each of the other illuminants with which work must be done, once for all. For instance, in the

20

photometry of tungsten lamps, it is not advisable to compare each individual lamp with a carbon standard of redder color value, but to compare the tungsten lamp with tungsten standards which have been standardized through a large number of comparisons by different observers against the carbon standard and in the standardization of which the color gap is spanned once for all.

In this connection Dr. Hyde has made the important suggestion that standards of different color values can be made as required by the use of standardized color screens which are interposed between the lamp of standard color and the lamp to be photometered. For instance, in the photometry of arc lamps a light blue-colored glass would be interposed between the incandescent lamp which serves as a working standard and the photometer, thereby bringing the tint on both sides of the photometer to the same value. The effect of this color screen will have been very carefully studied photometrically by a very large number of observers, and the reduction factor introduced by interposing the color screen will have been determined.

Photometers differ among themselves in their adaptability to heterochrome work. The photometer which is best adapted to homochromatic work is not necessarily the one which is most satisfactory for heterochrome work. A simple equality of brightness photometer is not in general found as sensitive as a contrast photometer and a photometer in which there is no mingling of the lights in the two fields is not so easy to use as one in which there is a certain degree of color mixing. Of all the simple photometers ordinarily used the Leeson disc seems to be most satisfactory for work where color differences are present. Through the translucency of the paper the lights are somewhat mingled, and consequently the color contrasts do not appear so strong.

Visual Acuity

Another method used in the evaluation of lights of different color is the so-called visual-acuity method, referred to in the beginning of the first lecture. This method depends upon the fact that with the eye in a normal condition the limit of field brightness with which the eye is able to distinguish objects in the field is a fairly sharp one. For instance, having a printed page with letters of a certain size on white paper, the eye is just able to distinguish the letters with a given degree of illumination. With